Preinstalled Sealant for Prefab Components

Oak Ridge National Laboratory
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Project Summary

Timeline:
Start date: August 1, 2020
Planned end date: July 31, 2023

Key Milestones
July 31, 2021: Synthetized a pressure-triggered sealant that cures in ~4 hours at room temperature.
July 31, 2023: Synthetized a pressure-triggered sealant with adhesion strength ≥20 lb/inch after 5 days curing at 20°F

Budget:
Total Project $ to Date:
• DOE: $1M
• Cost Share: ~$50K
Total Project $:
• DOE: $1M
• Cost Share: $250K

Key Partners:

Project Outcome:
Sealant that is installed at prefab plants and is pressure-activated at the jobsite to improve installation speed and quality of prefab components, reduce energy waste due to air leakage through the building envelope, and decrease assembly cost.
Team

Diana Hun, Pengfei Cao, Tomonori Saito, Dennis Michaud, William Lentlie

Jiancheng Luo, Zoriana Demchuk

Material Synthesis

Scaleup and Deployment

Autonomous Self-Healing Elastomers with Unprecedented Adhesion Force
doi.org/10.1002/adfm.202006298

Specializes in developing technologies for buildings

110+ years supplying building products

40+ years designing and building sustainable homes

U.S. DEPARTMENT OF ENERGY OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY
Prefab construction has been gaining momentum because assembly is efficiently done in controlled environments with quality control enforcement.

A main deficiency in prefab construction is joint sealing at the jobsite to maintain continuity of the air and water barriers.

Time-efficient, high-performance air sealing techniques are needed because air leakage is responsible for ~13% of the energy used in homes and ~6% of the energy used in commercial buildings.

Improvements in productivity will make prefab construction more affordable.

Current Joint Sealing Techniques

- Tapes
- Caulks and spray foams
- Gaskets

- Very time consuming
- Highly dependent on the installer
- Negate advances in productivity achieved at prefab plants
**Goal:** Develop sealant that is installed at the prefab plant and is pressure activated at the jobsite to improve installation speed and performance of the air barrier system.

**Adhesive polymer:** adheres sealant to prefab component
**Curing and reactive agents:** two component curing reaction
**Microcapsules:** separate reactive agents from curing agents
Impact

• BTO’s Advanced Building Construction (ABC) Initiative aims to increase affordability of energy efficiency and decarbonization through higher productivity.

• Prefab construction has been successful in increasing productivity at manufacturing plants.

• Onsite assembly of prefab components lacks innovation
  – Hinders performance and affordability
  – Assembling the air barrier system with prefab components is one of the most time-consuming tasks at the jobsite

• Air infiltration is responsible for ~4% of total energy used in the US.

• Preinstalled sealant for prefab construction
  – Enables annual energy savings of ~665 TBU from reductions in infiltration
  – Increases affordability of prefab construction

Productivity and Technological Innovation

<table>
<thead>
<tr>
<th>Industry</th>
<th>Circa 1940s</th>
<th>Circa 2016</th>
<th>Productivity Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td></td>
<td>1,512</td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td>760</td>
<td></td>
</tr>
<tr>
<td>Retail</td>
<td></td>
<td>699</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Cumulative real growth in the US, %, 1947-2010
1. Set initial sealant requirements based on feedback from industry partners

2. Synthesize adhesive polymers and test properties, e.g., adhesive force, mechanical properties

3. Identify curing system with high adhesion and tunable curing time

4. Synthesize microcapsules with tunable size and load reactive agent inside microcapsules

5. Demonstrate prototype of pressure-triggered sealant

6. Co-optimize required parameters to meet specs
## Progress: Specs Based on Industry Input

<table>
<thead>
<tr>
<th>Item</th>
<th>Bensonwood and CertainTeed Criteria</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low VOC emissions</td>
<td>California standards</td>
</tr>
<tr>
<td>2</td>
<td>Adhesion strength (ASTM D794)</td>
<td>&gt;20 lb/inch</td>
</tr>
<tr>
<td>3</td>
<td>Activation pressure</td>
<td>10-100 Psi</td>
</tr>
<tr>
<td>4</td>
<td>Curing temperature and time</td>
<td>20 to 110 °F Separate panels in 30-minute window. Shift/slide panels in 1 hour window. 2 to 5 days max curing at constant 20 °F.</td>
</tr>
<tr>
<td>5</td>
<td>Service temperature</td>
<td>-20 to 180 °F</td>
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<tr>
<td>6</td>
<td>Low water permeability</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Life Expectancy</td>
<td>20 years</td>
</tr>
<tr>
<td>8</td>
<td>Max cured elongation (ASTM D412)</td>
<td>Aim for 200% but will try 500%</td>
</tr>
<tr>
<td>9</td>
<td>Max. joint movement (ASTM C719)</td>
<td>±25%</td>
</tr>
<tr>
<td>10</td>
<td>Max joint width</td>
<td>1/2&quot; to 3/4&quot;</td>
</tr>
<tr>
<td>11</td>
<td>Installation temperature at plant</td>
<td>60 to 80 °F</td>
</tr>
<tr>
<td>12</td>
<td>Resistance to compression/extension</td>
<td>±50%</td>
</tr>
<tr>
<td>13</td>
<td>Hardness (ASTM C661)</td>
<td>15</td>
</tr>
<tr>
<td>14</td>
<td>Tack-free time (ASTM C679)</td>
<td>2 hours or less</td>
</tr>
<tr>
<td>15</td>
<td>Cut, tear, abrasion resistance</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Ultra-Violet resistance</td>
<td>2 to 4 weeks outdoor exposure max</td>
</tr>
</tbody>
</table>
Progress: Adhesive Polymer with Self-Healing Properties

Purpose
• Allow formulation to adhere to the substrate
• Extend life-time of sealant (Spec: life expectancy > 20 years)
• Achieve high elongation (Spec: max cured elongation 50%-500%)

Requirements
• Inexpensive polymerization
• High stretchability (> 1500%)
• Low glass transition temperature
• Self-healable

Developed cost-effective approach for adhesive polymer that is highly stretchable and self-healable.
Progress: Curing System

**Purpose:** Two-part system that provides high adhesion force after curing.

**Requirements:**
- Commercially available materials
- Low volatile organic compound (VOCs)
- Tunable curing time

Selected non-toxic isocyanate based prepolymer as curing system with high adhesion force and tunable curing time.

**Investigated different two-part curing systems**

- **Isocyanate**
  \[ R\text{-NCO} + R\text{-NH}_2 \]
- **Epoxy**
  \[ R\text{-O} + R\text{-NH}_2 \]
- **Acrylate**
  \[ R\text{-C=O} + R\text{-NH}_2 \]

- Isocyanate system has the best adhesion performance
- Use non-toxic prepolymer instead of toxic monomers

**Tuning curing time**

- Fast reaction
- Slow reaction

**Curing agent (amine polymer wt %)**

<table>
<thead>
<tr>
<th>%</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing time @ room temperature</td>
<td>&gt;1 d</td>
<td>8 h</td>
<td>2-3 h</td>
<td>1 h</td>
</tr>
</tbody>
</table>
Progress: Microcapsules

Purpose of microcapsules: separate reactive agents from curing agents to prevent curing until force is applied.

Requirements
• Low cost and feasible
• Easy to scale-up
• Narrow-distributed microcapsule sizes
• Controllable size (tuning activation force)

Fabrication method

Microscopy image

Diameter vs. stirring speed

SEM Image

Developed encapsulation method with tunable diameters for reactive agents.
Progress: Preliminary Prototypes

Peel Test (ASTM C794)

- Achieved peel strength: 23.4 lb/inch (104.1 N/inch)
- Targeted strength: 20.0 lb/inch (89.0 N/inch)

Successful development of preliminary prototypes with satisfactory adhesion.
Remaining Project Work: Improve Robustness and Shelf-Life After Installation and Before Triggering

**Preliminary Results**

Decrease in peel strength

- **Freshly prepared sealant**
  - Peel strength: 23.4 lb/inch (104.1 N/inch)

- **After 3 weeks in open air**
  - Peel strength: 4.9 lb/inch (21.8 N/inch)

**Reason**: isocyanate becomes inactive due to water vapor penetration inside microcapsules

![Graph showing decrease in peel strength](graph)

**Possible solutions**

**Approach 1**: hydrophobic coating on sealant

- **Preinstalled sealant**
- **Coating**
- **Commercial or custom setup**

**Approach 2**: curing system that is not sensitive to water

- **Water sensitive**
- **Not water sensitive**

![Diagram showing reactive agent and adhesive polymer](diagram)
Curing time and temperature

**Target:** 1-7 days @ 20 - 110 °F. Will aim for a formulation that can span this temperature range.

**Approach:** tailor chemical composition in sealant formulation

![Diagram showing chemical components]

- Fast reaction: Amine polymer
- Slow reaction: Hydroxyl polymer
- Fast reaction: Isocyanate prepolymer

- Ratio of amine/hydroxyl
- Isocyanate content
- Adhesive polymer content
- Extra fillers

### Triggering force

Pressure ($P_{cr}$) is affected by the microcapsule size and shell thickness.

\[
P_{cr} = \frac{2Eh^2}{\sqrt{3(1 - \mu^2)}} \frac{1}{R^2}
\]

**Current triggered force:** 500 N

**Tunable force:** 100-1000 N

**Approach:**
- Determine required triggering force value
- Correlate and calibrate measured force with calculated value
### Remaining Project Work:
**Co-Optimize Various Required Parameters**

- Co-optimize mechanical, adhesive performance and other requirements.
- Continuously consult with industry partners to ensure scalability and practicality.

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Stakeholder Engagement

Deployment: industry partners providing guidance on scalability and implementation

- Helped shape the building products industry for more than 110 years.
- Subsidiary of Saint-Gobain, one of the world’s largest and oldest building products companies with strong commitment to decarbonization.
- North America’s leading brand of exterior and interior building products, and leader in the development of technologies that enable prefab construction.
- 60+ manufacturing facilities throughout the United States and Canada.
- 40+ years designing and building homes sustainably.
- Ultra-precise prefabrication to streamline the process, minimize waste and guarantee performance.

Dissemination

Invited presentation
ABC Summit
April 28-29, 2021
**Summary**

**Demonstrated**
- Use of low-cost components
- Self-healability
- High stretchability
- High adhesion

**Remaining work**
- Co-optimize adhesion force with other requirements

**Demonstrated**
- Encapsulation of reactive agent
- Tunability of capsule size
- Lab-scale scalability

**Remaining work**
- Low water vapor permeability
- Tune triggering force

**Demonstrated**
- Use of low-cost components
- High adhesion

**Remaining work**
- Tune curing temperature and time
- Improve robustness and shelf-life

**Overview**

- **Pre-installed Sealant**
  - Adhesive Polymer
  - Microcapsules
  - Curing System
  - Prototype

**Provisional patent application**
#63/145,517
ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 50,000+ ft² of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results
238 publications in FY20
125 industry partners
27 university partners
10 R&D 100 awards
42 active CRADAs

Thank you
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**Project Budget**

**Project Budget:**
**Variances:** NA
**Cost to Date:** $220K
**Additional Funding:** NA

### Budget History

<table>
<thead>
<tr>
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<th>August 1, 2020 – FY 2020 (past)</th>
<th>FY 2021 (current)</th>
<th>FY 2022 – July 31, 2023 (planned)</th>
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<tbody>
<tr>
<td>DOE</td>
<td>$300K</td>
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<tr>
<td>Cost-share</td>
<td>$50K</td>
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## Project Plan and Schedule

<table>
<thead>
<tr>
<th>No.</th>
<th>Deliverables/Milestones</th>
<th>Dates</th>
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<tbody>
<tr>
<td></td>
<td><strong>Task 1. Develop product requirements Document (PRD): Refine sealant requirements</strong></td>
<td></td>
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<tr>
<td></td>
<td>M1.1 Set initial sealant requirements with regard to installation in prefabricated components, curing temperature and time, adhesion strength, service temperature, life expectancy, elongation, VOC emissions, production scaleup, and material cost based on feedback from our industry partners.</td>
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<td></td>
<td><strong>Task 2. Synthesize, develop and optimize the pressure-triggered sealant</strong></td>
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<tr>
<td></td>
<td>M2.1 Identified at least three candidates for the epoxy-based and the urethane-based sealant systems that can cure in less than ~5 hours at ~73°F based on the literature and the team’s previous research on sealants.</td>
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<tr>
<td></td>
<td>M2.2 Synthesized microcapsules that can be used with the epoxy-based and the urethane-based sealant systems, and identified the variables that can be adjusted to tune the diameter and shell thickness of the microcapsules.</td>
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<td></td>
<td>M2.3 Synthesized a prototype for a two-component sealant in which the curing agent is in microcapsules that are dispersed in a hardener, and demonstrated that the prototype sealant is triggered by pressure and cures in ~4 hours at ~73°F. The prototype will consist of at least 10 grams so that preliminary peel strength tests can be conducted according to ASTM D4541.</td>
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<td></td>
<td><strong>Task 3. Tailor curing time at different temperatures</strong></td>
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<td></td>
<td>M3.1 Developed prototype sealants that expand the installation temperature to below freezing conditions, that is, it cures within 2 days at 0°F.</td>
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<td></td>
<td><strong>Task 4. Tailor triggering force</strong></td>
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<td></td>
<td>M4.1 Developed a bench-scale test setup that simulates how pressure will be applied by prefabricated components to activate the chemical reaction between the sealant components. The setup will also regulate the applied force so that the relationship between triggering force and peel strength can be studied and the minimum required force can be estimated.</td>
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<td></td>
<td>M4.2 Developed a pressure-triggered sealant that is activated by the pressure specified in the PRD. Measurements will be collected using the bench-scale test setup that was assembled for M4.1.</td>
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</tr>
<tr>
<td></td>
<td>M4.3 Developed a pressures-activated sealant that meets the activation pressure and curing time specified in the PRD under the guidance from our industry partners.</td>
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<td></td>
<td><strong>Task 5. Increase the robustness of the pressure-triggered sealant</strong></td>
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<tr>
<td></td>
<td>M5.1 Identified the parameters that need to be tailored to lower the probability that the sealant is damaged during handling. Scenarios that could damage the pre-installed sealant will be identified with input from our industry partners. For example, the sealant could be made more robust by lowering its tackiness so it does not stick to unintended surfaces while the prefabricated part is moved.</td>
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<tr>
<td></td>
<td>M5.2 Developed a more robust pressure-triggered sealant that withstands the damaging scenarios presented by our industry partners, that has the required triggering pressure and curing time according to the PRD, and adhesion strength &gt;10 lb/in.</td>
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<tr>
<td></td>
<td><strong>Task 6. Tailor stretchability of cured sealant</strong></td>
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<tr>
<td></td>
<td>M6.1 Elongation of the pressure-activated sealant that cured for 2 weeks at 73°F is greater than 100%.</td>
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<tr>
<td></td>
<td><strong>Task 7. Increase peel strength to ≥20 lb/in.</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M7.1 Synthesized a pressure-triggered sealant with adhesion strength ≥15 lb/in, and curing time and triggering force per the PRD.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M7.2 Synthesized a pressure-triggered sealant with adhesion strength ≥20 lb/in, elongation ≥100%, and curing time and triggering force per the PRD.</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Regular
- Go/No Go
- Completed
- Ongoing