Biobased Materials for Sustainable Temporary Disaster-Relief Housing

A.T. Michel\textsuperscript{1}, W.V. Srubar III\textsuperscript{2} and S.L. Billington\textsuperscript{3}

**ABSTRACT**

Temporary housing structures for natural-disaster victims are often assembled from readily available and inexpensive materials, such as engineered wood, plastics, and non-biodegradable foams. Past events have demonstrated that these structures often serve multiple purposes and remain in use longer than originally expected, resulting in persistent substandard housing with considerable post-use disposal implications. Alternative sustainable materials that exhibit adequate in-service performance and rapid post-use recyclability, reusability, or biodegradability present an opportunity to minimize ecological impacts of disaster relief housing applications. This research demonstrates that fully biobased, biodegradable structural insulated panels can be engineered to have competitive mechanical and thermal properties compared to wood, engineered wood, and insulating foams typically used in temporary disaster-relief housing structures.

**BACKGROUND & MOTIVATION**

While typologies of disaster-relief structures vary widely by geographic location, their function is universal – to help displaced victims of natural catastrophes transition from emergency shelters to permanent housing [1] by providing immediate relief from environmental conditions; contributing to safety, security, dignity, health, and well-being; enabling normal household activities; and bridging the gap until permanent housing is available [2]. Despite these benefits, temporary shelters are frequently built in disaster prone areas, heightening risks for already vulnerable populations. In addition, temporary housing can be expensive [3] and an unsound investment if permanent alternatives are forthcoming [4]. Materials used for these structures (e.g., wood, plywood, masonry, steel, sheet metal, insulation foam) have a much longer lifespan than their intended period of use [5]. Thus, transitional housing, which typically has an expected lifespan of 6 months to 3 years, often becomes substandard permanent housing [6].

Tents and pre-manufactured modular dwellings frequently provide interim shelter while permanent structures are built. A clear example is the Chinese response to the 2008 Sichuan earthquake, where over 650,000 temporary housing units were built from metal-faced polyurethane insulated panels [7]. While effective for meeting the immediate needs of the community, these structures were neither the most cost-effective nor environmentally sustainable solution, and the affected regions are now burdened with their deconstruction and disposal. Similarly, two years following the 2010 Haiti earthquake, over half-a-million Haitians still resided in tent encampments originally intended to last for only a few months [8].

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The sustainability and effectiveness of transitional housing can be improved through the use of innovative, environmentally-friendly materials and structural systems. The research presented herein investigates materials that (a) decrease reliance on nonrenewable resources (e.g., polyolefin-based plastics), (b) satisfy multiple design criteria (e.g., structural, thermal), and (c) can be readily and rapidly transformed into another functional product (i.e., recycled, reused, or biodegraded) at the end of their useful life.

**BIOBASED MATERIALS & COMPONENTS**

Biobased plastics, composites, and their structural assemblies are of particular interest for disaster relief structures [9]. Biobased plastics can be derived from plant byproducts (e.g., poly-lactic-acid (PLA)) or synthesized microbially (e.g., polyhydroxyalkanoates (PHA)). When combined with natural fibers, such as hemp, jute, and wood fibers, biopolymers serve as the matrix for composite materials with advantageous mechanical properties [10]. These composites can be developed as structural sections (e.g., box- and I-beams) or assemblies (e.g., structural insulated panels), and used as replacements for conventional building materials.

Biobased materials are favored for use in disaster relief structures for their potentially low environmental impact, ease of post-use disposal, and, in some instances, closed-loop lifecycle [11]. For example, some PHA biopolymer composite materials rapidly biodegrade in anaerobic conditions commonly found in wastewater treatment facilities [12]. Methane gas, the primary byproduct of this degradation, can be used as a fuel source or as a feedstock to grow additional biopolymer, facilitating a closed-loop lifecycle. Additionally, due to the global availability and economy of natural fibers (e.g., hemp, jute, esparto, wood fiber), biobased composite materials can be produced in virtually any geographic location [13-15].

In this research, biobased sandwich panels have been investigated as materials for temporary shelters for their attractive mechanical, insulating, and environmental properties. The biobased composites investigated herein are made from polyhydroxybutyrate-co-hydroxyvalerate (PHBV) biopolymer reinforced with hemp linen (HL) and jute burlap (JB). Structural sandwich panels with PHBV-HL and -JB face sheets and a biobased foam core (BIO) are constructed by adhering the composite sheets to the exterior of the biobased foam using a bio-derived adhesive. The constituent components of the sandwich panel are presented in Figure 1a; additional details about the materials and construction methods are documented elsewhere [16].

**Mechanical Properties**

The mechanical properties of these biobased composites are comparable to those for wood and engineered wood, which are commonly used for transitional housing. However, as shown in Table 1, these biobased composites are 2-3 times as dense as wood products. Thus, the specific properties (i.e., those normalized by density) of the biobased composites are lower than those for conventional construction materials. Biobased composites can however achieve higher strength and stiffness by optimizing their structural geometry, such as in sandwich structures. Figure 1 demonstrates that, for certain span lengths, the mass of biobased sandwich panel required to provide a specified target stiffness is less than equivalent sections of wood, plywood, and oriented strand board (OSB). This result suggests that biobased sandwich panels can be competitive with conventional construction materials on the basis of specific mechanical properties. For temporary structures, these findings indicate that biobased composite sandwich panels may be suitable structural alternatives to traditional wood studs and plywood sheathing.
Table 1: Flexural modulus, $E'$, density, $\rho$, and specific modulus, $E'/\rho$, for several common construction materials and typical PHB-hemp linen biobased composites [16].

<table>
<thead>
<tr>
<th>Material</th>
<th>$E'$ (GPa)</th>
<th>$\rho$ (g/m$^3$)</th>
<th>$E'/\rho$ (GPa-m$^3$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>9.7 ± 1.8</td>
<td>0.42 ± 0.06</td>
<td>23.1 ± 3.3</td>
</tr>
<tr>
<td>Plywood</td>
<td>7.6 ± 0.5</td>
<td>0.48 ± 0.07</td>
<td>16.2 ± 2.7</td>
</tr>
<tr>
<td>OSB</td>
<td>5.7 ± 0.9</td>
<td>0.65 ± 0.06</td>
<td>8.8 ± 1.5</td>
</tr>
<tr>
<td>PHBV-HL</td>
<td>5.6 ± 0.4</td>
<td>1.25 ± 0.03</td>
<td>4.5 ± 0.1</td>
</tr>
</tbody>
</table>

Figure 1: Mass, $M$, of OSB, plywood, PHBV-HL composites, and biobased sandwich panels normalized by the mass of wood, $M_{\text{wood}}$, required to achieve an equivalent four-point bending stiffness as a function of span length, $L$.

Thermal Properties

The properties of thermal conductivity, $\kappa$, and resistance, $R$, for the biobased composite face-sheets, foam cores, and the structural insulated panels, as determined by thermal conductivity analysis, are presented in Table 2, alongside the properties for wood, plywood, OSB, medium density fiberboard (MDF), OSB-expanded polystyrene (EPS) SIPs, and OSB-XPS SIPs. The biobased materials exhibit equivalent or superior thermal insulating properties when compared to other building materials. For example, the PHBV-HL face-sheets are demonstrated to have greater thermal resistance than wood, plywood, OSB, and MDF by a factor of approximately 1.5-2. Similarly, the biobased BIOF foam is nearly equivalent to the synthetic in terms of thermal properties. These observations suggest that the proposed biobased materials can be considered competitive with traditional building materials on the basis of thermal resistance.

Table 2: Measured thermal properties for the investigated foam cores, composite face-sheets, and sandwich panels compared to conventional building envelope materials.

<table>
<thead>
<tr>
<th>Investigated Materials</th>
<th>$\kappa$ (W/m-K)</th>
<th>$R$ (m$^2$K/W)</th>
<th>Conventional Materials</th>
<th>$\kappa$ (W/m-K)</th>
<th>$R$ (m$^2$K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPS</td>
<td>0.029 ± 0.003</td>
<td>34.6 ± 4.0</td>
<td>Wood</td>
<td>0.09</td>
<td>11.2</td>
</tr>
<tr>
<td>BIOF</td>
<td>0.034 ± 0.002</td>
<td>29.6 ± 1.4</td>
<td>Plywood</td>
<td>0.12</td>
<td>8.3</td>
</tr>
<tr>
<td>PHBV-HL</td>
<td>0.063 ± 0.002</td>
<td>15.8 ± 0.4</td>
<td>OSB</td>
<td>0.12</td>
<td>8.3</td>
</tr>
<tr>
<td>PHBV-JB</td>
<td>0.106 ± 0.001</td>
<td>9.5 ± 0.2</td>
<td>MDF</td>
<td>0.10</td>
<td>10.0</td>
</tr>
<tr>
<td>PHBV-XPS</td>
<td>0.033 ± 0.003</td>
<td>29.9 ± 2.8</td>
<td>OSB-EPS</td>
<td>0.042</td>
<td>23.9</td>
</tr>
<tr>
<td>PHBV-BIOF</td>
<td>0.041 ± 0.005</td>
<td>24.5 ± 2.9</td>
<td>OSB-XPS</td>
<td>0.032</td>
<td>31.7</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Temporary and transitional structures serve a critical role for communities recovering from natural catastrophes. Alternative sustainable materials were suggested for mitigating the environmental impact of these structures. Both natural fiber composites and sandwich panels were demonstrated to exhibit competitive specific stiffness properties and equivalent or superior thermal insulating properties to conventional building materials. These combined results suggest that certain biobased materials, which can be constructed using locally available resources, are viable for use as the primary structural and insulating systems of temporary structures. Continued research efforts are needed to compare the environmental (lifecycle) performance of these materials with their conventional counterparts and to evaluate for large-scale fabrication.

REFERENCES