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PII: S2468-0257(18)30018-9
DOI: 10.1016/j.gee.2018.05.004
Reference: GEE 116

To appear in: Green Energy and Environment

Received Date: 26 January 2018
Revised Date: 1 May 2018
Accepted Date: 31 May 2018

Please cite this article as: D. Mathis, P. Blanchet, V. Landry, P. Lagière, Thermal characterization of bio-based phase changing materials in decorative wood-based panels for thermal energy storage, Green Energy & Environment (2018), doi: 10.1016/j.gee.2018.05.004.

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Thermal characterization of bio-based phase changing materials in decorative wood-based panels for thermal energy storage.

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Bio-based PCM

HDF

MDF

High latent heat storage
wood-based panel loaded with
a bio-based PCM
Abstract
Decorative wood panels containing pouches of bio-based phase changing materials (PCMs) were prepared. Three different PCM mixtures were used: a blend of capric and lauric acids as well as two commercial products, Puretemp®20 and Puretemp®23 (Puretemp). The panels consist of engraved Medium Density Fiberboard (MDF) filled with a plastic pouch filled with PCM. High density fiberboard (HDF) was used on top of the panels to enclose the PCM pouches. PCM mixtures were first tested by differential scanning calorimetry (DSC). Phase change temperature and total heat storage of the panels were measured for both fusion and solidification with a Dynamic Heat-Flow Meter Apparatus (DHFMA). DSC and DHFMA results were compared, allowing a better understanding of results gathered from these two techniques. DSC calibration has been revealed important when assessing PCMs. The panels present a phase change temperature and a latent heat storage suitable for buildings applications. The panel made with Puretemp®23 presented the highest energy, with 57.1 J/g. Thermal cycling was conducted on the panels to investigate thermal reliability, which revealed small modifications of thermal properties for two products. For all cases, latent heat was found stable. Hygro-mechanical behavior of the panels was also evaluated as these where designed to be aesthetic decorative panels. This study exposes the potential of a new type of wood-based panels loaded with PCM for thermal energy storage and brings overall knowledge about PCM products thermal characterization.

Keywords: PCM; wood; biosourced; fatty acids; DHFMA

1. Introduction
Phase change materials (PCMs) are recognized as an effective way to enhance buildings thermal mass [1]. As melting occurs, a significant amount of energy is stored. This energy is then released in the building by solidification as interior temperature decreases. If implemented carefully, PCM products can permit to achieve energy savings in the heating period [2-3] and reduce buildings overheating in summer [4-5]. A wide range of solutions, either active or passive, have been experimented [6] with PCMs.

Potential benefits of PCM wallboards have already been demonstrated across multiple full-scale experimental studies [7-9]. An advantage of wallboards is their proximity with the interior air of buildings, compared to solutions that implement PCMs within the walls. As thermal comfort depends on operative temperature, panels containing PCMs could have a great contribution by keeping wall temperatures within the comfort zone [10]. They can store energy by receiving direct sunlight or according to the convection inside the building [11].
There are only a few trials of PCM composites using wood as substrate. Although, wood is a renewable material that could lead to lower embodied energy products [12]. Xi Guo et al. (2016) prepared wood plastic composites (WPC) by integrating microencapsulated dodecanol into wood flour with high-density polyethylene (HDPE). They obtained a composite with a modulus of elasticity between 0.9 and 2.2 GPa, and 20.3 J/g of latent heat [13]. Mechanical properties were decreasing with the increase of PCM microcapsules ratio. Jeong et al. (2012) proposed to add microencapsulated PCMs (MPCMs) in wood adhesives to enhance wood flooring thermal mass. Bonding strength remained good, but thermal mass enhancement was low [14]. Barreneche et al. (2017) impregnated wood with paraffinic PCMs RT-21 and RT-27 from Rubitherm® [15]. They obtained a composite with a latent heat of 20.62 J/g for a PCM mass proportion of 29.9%. To avoid any leakage, they encapsulated the wood with a polystyrene solution in organic solvent. However, wood is a material that can age and undergo dimensional variations. Applying a coating that will stabilize his structure may cause later damages and thus leakage.

The composites previously cited are made with a large proportion of non-renewable resources, such as HDPE, polystyrene and paraffinic PCMs. Furthermore, the mass of MPCMs that can be added into WPC is limited because of its negative effect on mechanical properties [13]. This leads to a composite with a low mass fraction of PCM, thus a limited latent heat. In this context, wood decorative panels containing pouches of bio-based organic PCMs were designed. A simple design would lead to an ease for recycling.

Various types of PCMs have been used over decades [16]. Organic PCMs are mainly constituted by paraffinic and bio-based compounds. Inorganic PCMs includes salt hydrates and metallic compounds. Fatty acids are widely used organic PCMs. They are used as binary eutectic mixtures in order to have suitable phase change temperatures. Main advantages of these eutectic mixtures are a low supercooling, chemical stability and possibly low environmental impact [17-18]. As if binary mixtures are made of two compounds, there is no segregation over phase change cycles. [19]

Thermal characterization of PCMs can be achieved with several techniques [20]. Differential Scanning Calorimetry (DSC) is a fast and efficient technique that has been widely used, however it is associated with some disadvantages or uncertainties regarding PCM evaluation. There is still no consensus about how DSC test and calibration should be performed for PCM testing [21-22]. However, the calibration will have an impact on the melting and solidifications temperatures. Any error will lead to a wrong estimation of the PCM behavior and thus modify the strategies required for a successful integration in a building. In addition, DSC only allows to test small samples. In 2014, ASTM introduced the new test standard C1784 to measure thermal storage properties of PCM-enhanced products of a larger scale based on the Dynamic Heat-Flow Meter Apparatus (DHFMA) principle and method. This methodology requires a longer
time of characterization than DSC but allows to avoid some of its constraints [23]. With DSC, thermal inertia of the samples affects their phase change temperature, which is not the case with DHFMA. In 2015, Shukla and Kosny characterized five PCM-integrated products to fill the lack of test data and describe a reliable procedure for the DHFMA method [23]. However, scientific literature about this innovative and efficient new methodology is still lacking. A comparison between DSC and DHFMA results would allow a better understanding of PCM thermal characterization. Determining accurately the thermal properties of PCM products is critical to achieve successful implementations within buildings [24].

For this study, a eutectic mixture of capric and lauric acids was prepared. In addition, commercial products from Puretemp® were used. PCMs were first tested by DSC. Then, wood-based panels were formed and characterized. The DSC results for PCMs mixtures were compared to the DHFMA results for panels. This comparison will allow a better understanding of thermal characterization of PCM products. Finally, thermal and hygro-mechanical behavior of the panels was assessed.

This study aims to determine the thermal storage capacity and hygro-mechanical behavior of decorative wooden panels loaded with different bio-based PCMs. An innovative comparison between DSC and DHMFA tests is presented. Results of the present study will allow to assess about the potential of such panels for thermal energy storage and contribute to the overall knowledge of the thermal characterization of PCM products.

2. Material and methods

2.1 Materials

2.1.1 Phase change materials

Capric (CA) and lauric (LA) acids were purchased from Sigma Aldrich (Canada). In order to simulate an industrial use with reasonable costs, a purity of 95% was selected. According to Sigma Aldrich, melting range of CA is 27 - 32 °C and its density is 0.893 g/cm$^3$ at 25 °C; melting point of LA is 43.8 °C and its density is 0.49 g/cm$^3$ at 20 °C.

The two other PCMs used in this study were commercial products. They were bought from Puretemp® (USA). Puretemp® products are USDA certified 100 % bio-based products. Exact composition is not known as these products are under patent protection. Two products used were: PT20 and PT23, respectively with phase change temperatures of 20°C and 23°C.

2.1.2 Wood Panels
Medium Density Fiberboard (MDF) were obtained from Uniboard® (Canada). They were used as the main component of the decorative panels developed. MDF is a widely used wood panel prepared from wood fibers combined and a urea formaldehyde resin by applying high temperature and pressure.

On the upper face of the panels (fig 1b), High Density Fiberboard (HDF) was chosen, for several reasons. As it constitutes the face of the panels that will face the interior of the building, this part needs to have a good mechanical and physical properties. In addition, the layer facing the interior needs to be thin. The thinner this layer is, the better the thermal exchange between the PCM and the interior air is. Furthermore, HDF can be found in low thickness on a commercial scale. HDF Fibrex® from the company Goodfellow® (Canada) was used.

Main properties of wood components used are listed in Table 1.

Table 1: Properties of wood panels as provided by the suppliers

<table>
<thead>
<tr>
<th></th>
<th>Density (kg/m³)</th>
<th>Module of rupture (N/mm²)</th>
<th>Resin</th>
<th>Thickness (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDF</td>
<td>525</td>
<td>15</td>
<td>Urea-formaldehyde</td>
<td>13 mm</td>
<td>Uniboard®</td>
</tr>
<tr>
<td>HDF</td>
<td>900</td>
<td>42.7</td>
<td>Urea-formaldehyde</td>
<td>5.5 mm</td>
<td>Goodfellow®</td>
</tr>
</tbody>
</table>

2.2 Samples preparation

2.2.1 Phase change materials

A blend of capric acid and lauric acid was prepared by mixing them at 40°C for 10 minutes. Eutectic point is reached when the two components melt simultaneously. On the phase diagram and therefore on the DSC enthalpy curve, this corresponds to a single peak of fusion and solidification. Eutectic is the composition for which the melting point is the lowest. In the literature, eutectic composition was ranging from 61.5-38.5 % to 67-33 % for CA/LA ratio [18].

The commercial Puretemp® mixtures were used as received, no preparation was required.

2.2.2 Panels preparation

In order to prepare the wood panels, PCM mixtures were encapsulated first. This was achieved using a vacuum machine and 0.08 mm thick polyethylene bags.
MDF panels 13 mm thick were grooved to contain the PCM pouches in it. 5.5 mm thick HDF was glued with a PVA adhesive to the MDF to close the panel. Then, a maple veneer was manually applied using a pressure-sensitive adhesive. Finally, panels had an overall thickness of 19.5 ± 0.5 mm. in the fig 1 a), a sawn panel so the PCM pouch is visible. A sketch of the assembly is given in fig 1 b).

Figure 1: a) Panel with the PCM pouch b) sketch of a wood/PCM panel

2.3 Characterization of the panels
2.3.1 DSC

Measurements of PCMs melting, freezing temperatures and latent heats were performed by DSC (METTLER Toledo 822E, Canada). The DSC instrument was calibrated with indium at 10°C/min. Measurements were performed at 10°C/min constant heating rate, with a temperature range from 0°C to 50°C under a constant stream of nitrogen of 80 ml/min. For each compound, three samples were tested. Results are the average of three measurements given with the standard deviation. Aluminum crucibles were filled with a mass of 4 mg to 6 mg.

There is no consensus about the DSC heating rate when testing PCM samples [21-22], as the result for transition temperatures are dependent of the heating rate [25]. A rate of 10 °C/min was selected. Some studies report that lower heating rates or a step-by-step method could enhance DSC test accuracy. [26-28]. An explanation for this is that PCMs embody a large amount of latent heat. This can cause lag if the test is performed too fast, as it generates a temperature gradient in the sample [29]. However, preliminary
DSC tests were conducted on distilled water with hermetic aluminum crucibles. These tests revealed that lowering the heating rate was giving wrong ice melting temperature values. A 1°C/min heating rate was giving a melting point of 2.78°C while distilled water melts at 0°C. This could be explained by the large difference of melting point between the material used for calibration and the PCMs. [30]. Indium melts at 156.60 °C [31] while the PCMs used melts around 20°C. The approximation made by the DSC could bring shifted results.

In addition, calibrating with a metal to assess organic materials properties could bias the accuracy. The main causes could be that a liquid metal will have a higher thermal conductivity than an organic liquid [32]. Thus, the DSC sensors would receive lately the heat from the liquid PCM. This delay could lead to a higher melting point, such as measured for distilled water in the calibration.

Distilled water has a melting point and latent heat closer to the PCMs than Indium. Then, considering that the 10 °C/min rate was measuring a melting temperature of water at 0.13 °C, this rate was selected for the tests.

For both freezing and melting points, onset temperatures were considered. The latent heat was determined by numerical integration of the peak. Results are the average of three measurements. For each test, cooling was conducted first so the samples would have the same solidification rate.

2.3.2 Heat storage measurements

Total heat storage measurements were carried out on the panels with a DHFMA method, using a Lasercomp Fox FX314 (TA instruments, USA). Tests were conducted in accordance with ASTM C1784 “Standard Test Method for Using a Heat Flow Meter Apparatus for Measuring Thermal Storage Properties of Phase Change Materials and Products” (ASTM, 2016). This experimental method allows to characterize larger samples than DSC, such as panels or flooring solutions. Total heat storage is the addition of sensible heat storage of both wood and PCM plus the latent heat storage of the PCM.

For each panel, cooling was conducted first so the PCMs can have the same solidification rate. 30 by 30 cm panels were placed in the apparatus. Upper and lower plate were maintained at the same temperature. A ramp of temperature was applied from 10 degrees above the estimated melting temperature, until 10 degrees below this temperature. According to ASTM C1784, temperature steps must be 1.5 ± 0.5°C. For these tests, 1.2°C step was chosen, so the test could have sufficient precision to avoid saturation. The enthalpy measured is the total heat storage. It includes wood specific heat, PCM specific heat in both liquid and solid state, plus the phase change enthalpy.
Every total heat curve is the result of two replicate runs on a panel. Two tests are conducted with a 0.6°C temperature shift. Then, the two tests are merged to obtain the final total heat curve. This methodology, described in ASTM C1784, allows to enhance DHFMA test accuracy.

For both freezing and melting points, onset temperatures were considered. They were obtained considering initial baselines and their intersections with the maximum slope of the total heat curve, as shown in fig 2. Tm and Ts respectively refer to melting and solidification temperatures. Heat storage for both fusion and solidification were calculated using the data provided by the FOX FX314 considering a transition range of 3 degrees. For each PCM mixture, two panels were tested. Results are the average of the two panels.

A correction must be applied on the results given by the Fox FX314. Indeed, the heat flux meter are on the center of each plate. It sees and takes measurements in the central part of the panel that is a laminated composite of 3 materials: MDF, PCM pouch and HDF. However, the panel is not horizontally homogenous. Indeed, the panels are made with a wood edge allowing MDF and HDF to be glued, ensuring mechanical stability. In order to have real total heat storage, results must be corrected using the surface percentage of the panel that does not embody any PCM. To achieve this, MDF and HDF specific heats were measured and a correction was applied.
2.3.3 Thermal cycling

PCM panels need to be energetically efficient over years. In order to achieve this efficiency, their properties need to remain constant over time. Indeed, fusion temperature and fusion enthalpy are chosen according to the climatic zone and the house architecture. Any variation in the material properties would make the energetic calculus and previsions obsolete.

In the literature, thermal reliability of PCM products is tested by cycling the materials. It starts from a few dozen to several thousand [33]. In this study, each panel was thermally cycled 200 times. One cycle includes one fusion and one solidification. Cycling was achieved using the aging module of the Lasercomp Fox FX314. To ensure that phase transitions were completed, heat flux was measured using the aging module of the Lasercomp Fox FX314.

2.3.4 Moisture behavior

The wood-based PCM panels are prepared to cover interior walls of buildings. Thus, they need to be aesthetics. In this context, a stability in their design over time must be kept to ensure the decorative function. However, the entrapped pouch of PCM and its effects on moisture management needed to be known. Moisture could degrade the panels and drive surface defects. In order to characterize this, moisture behavior tests were conducted with two samples: PCM panels and control panels. PCM panels were those described previously, filled with CA and LA acids. As a control, panels of the same size but without the hole and the PCM pouch were used.

Tests were conducted in three phases: stabilization under an atmosphere at 20°C / 80 % relative humidity (RH), then 20°C / 20 % RH and then again 20°C / 80 % RH. Each phase lasted 21 days. Measurements were done for each cycle after 4, 7, 14 and 21 days. Similar tests were conducted by Blanchet et al. to assess moisture behavior of engineered wood flooring [34]. This methodology allows to assess the moisture behavior of similar products under high (summer) and low (winter) relative humidity in North America. All sides of the panel were exposed to the water.

Nine surface points were considered on the panels, distributed as shown in fig 3. A 3D portable coordinate measuring arm, Fusion FaroArm (FARO, Canada) was used to measure the deformation each week. Measurements were done using the probing mode with a probe diameter of 6 mm.
In order to assess panels global deformation, surface points were grouped. Group A includes points 1-6-7, group B is for points 2-5-8 and group C is for points 3-4-9. The average position of points was calculated for each group at each day of measure. This allows to trace curves representing the average shape of the panels over cycles.

In addition, the amplitude of deformation for each cycle was assessed. Amplitude is the highest measure minus the lowest measure within all the points of the panel. This was calculated for each panel at each cycle. Then, the average amplitude for both control and PCM panels were calculated.
3. Results and discussion

3.1 DSC of PCM mixtures

DSC results performed on the acids used in this study was confirmed to be eutectic at 64% of capric acid and 36% of lauric acid. Thermal properties of PCM measured with DSC tests are presented in Table 2.

### Table 2: DSC results

<table>
<thead>
<tr>
<th></th>
<th>Capric (64%)/Lauric (36%)</th>
<th>PT20</th>
<th>PT23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point onset (°C)</td>
<td>19.7 ± 0.1</td>
<td>18.6 ± 0.1</td>
<td>22.3 ± 0.2</td>
</tr>
<tr>
<td>Latent heat of fusion (J/g)</td>
<td>128.7 ± 1.7</td>
<td>174.6 ± 2.2</td>
<td>197.9 ± 13.2</td>
</tr>
<tr>
<td>Solidifying point onset (°C)</td>
<td>23.5 ± 0.3</td>
<td>23.8 ± 0.1</td>
<td>25.6 ± 0.2</td>
</tr>
<tr>
<td>Latent heat of solidification (J/g)</td>
<td>124.9 ± 1.5</td>
<td>172.5 ± 1.3</td>
<td>200.1 ± 12.4</td>
</tr>
</tbody>
</table>

Results for the melting point of the capric/lauric (CA/LA) mixture are in accordance with literature, as presented in Table 3. However, solidifying temperatures are higher than expected. Indeed, organic PCMs usually show a little supercooling [35-36]. This higher solidifying temperature could result from differences in the methodology used with DSC tests.

### Table 3: Comparison of CA/LA mixtures properties

<table>
<thead>
<tr>
<th>Eutectic composition</th>
<th>Purity</th>
<th>Melting point onset (°C)</th>
<th>Latent heat of melting (J/g)</th>
<th>Solidifying point onset (°C)</th>
<th>Latent heat of solidification (J/g)</th>
<th>Ref</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA/LA (64-36 w%)</td>
<td>95 – 95 %</td>
<td>19.7</td>
<td>128.7</td>
<td>23.5</td>
<td>124.9</td>
<td>Present study</td>
<td>DSC Mettler Toledo Calibrated Indium 10°/min Test ramp 10°/min</td>
</tr>
<tr>
<td>CA/LA (64-36 w%)</td>
<td>98 – 98 %</td>
<td>19.6</td>
<td>150.0</td>
<td>19.4</td>
<td>149.0</td>
<td>[37]</td>
<td>DSC PerkinElmer Jade Calibrated Indium Test ramp 5°/min</td>
</tr>
<tr>
<td>CA/LA (62-38)</td>
<td>-</td>
<td>18.6</td>
<td>121.0</td>
<td>-</td>
<td>-</td>
<td>[38]</td>
<td>DSC, Q20 Test ramp 2°C/min</td>
</tr>
</tbody>
</table>

For commercial products, PT20 and PT23, latent heats were close to the values of the technical data sheets but the fusion temperature found were lower. Results are shown in Table 4. As theses mixtures are made from agricultural waste, their properties may
vary a little over batches. Indeed, two different batches were tested and had different melting temperatures. The results presented here are from the batch that was used to prepare the panels.

### Table 4: Puretemp® products properties

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Melting point onset (°C)</th>
<th>Latent heat of melting (°C)</th>
<th>Experimental method</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT20</td>
<td>18.7 ± 0.2</td>
<td>179 ± 4</td>
<td>DSC Mettler Toledo Calibrated Indium 10°/min Test ramp 10°/min</td>
<td>Current study</td>
</tr>
<tr>
<td>PT20</td>
<td>19.9 ± 0.3</td>
<td>171</td>
<td>DSC Q2000 Test ramp 1°/min</td>
<td>Puretemp®</td>
</tr>
<tr>
<td>PT23</td>
<td>22.1 ± 0.1</td>
<td>193 ± 20</td>
<td>DSC Mettler Toledo Calibrated Indium 10°/min Test ramp 10°/min</td>
<td>Current study</td>
</tr>
<tr>
<td>PT23</td>
<td>23.4 ± 0.2</td>
<td>201</td>
<td>DSC Q2000 Test ramp 1°/min</td>
<td>Puretemp®</td>
</tr>
</tbody>
</table>

3.2 Panels thermal properties

Total heat storage curves for one of each panel are shown in **fig. 4**

![Total heat storage curves](image-url)
For each panel, total heat storages over a transition range of 3°C, fusion temperature and solidification temperature were calculated. Results are given in Table 5.
Panel PT23 exhibits the highest heat storage. DSCs tests also indicated that PT23 mixture had the highest heat storage. For each panel, solidification temperature is lower than fusion temperature. It is concordant with the supercooling often encountered with organic PCMs. [31-32]

Solidification total heat is higher than fusion total heat. This can come from the fact that fusion takes place within a larger temperature range. As the total heat is here calculated over 3°C, it does not allow to consider the whole fusion heat. Extending this range of calculus would have included more specific heat. Therefore, the 3°C range was kept.

Repeatability of the FOX FX314 measurements was high. Three tests on the same panels gave the exact same solidification temperature. This was possible by the fact that the tests were conducted step-by-step every 0.6°C. This methodology leads to an incertitude that depends on the steps width. Smaller steps would have led to a lower incertitude.

For the PT20 panel, the two samples had different solidification temperatures with a 1.2°C shift. The two samples were tested with an interval of 7 months. A reason for this shift could be that the mixture PT20 aged. Indeed, the second panel tested has the same solidification temperature than the panel that was thermally cycled. Thermal cycling performance will be presented in the next section. As the PT23 product was stored in a laboratory where temperature can fluctuate, it is possible that cycles of fusion and solidification occurred naturally.

The Table 6 presents a comparison of several phase-change wallboards in literature. Wood-based panels from the present study exhibit characteristics comparable to existing products and embody the highest fusion heat for a wood-based composite.

<table>
<thead>
<tr>
<th></th>
<th>Panel CA/LA</th>
<th>Panel PT20</th>
<th>Panel PT23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point onset (°C)</td>
<td>20.6 ± 0.1</td>
<td>20.2 ± 0.1</td>
<td>22.2 ± 0.2</td>
</tr>
<tr>
<td>Heat of fusion (J/g)</td>
<td>47.5 ± 1.6</td>
<td>56.9 ± 1.8</td>
<td>57.1 ± 0.5</td>
</tr>
<tr>
<td>Solidifying point (°C)</td>
<td>20.5 ± 0.1</td>
<td>19.8 ± 0.6</td>
<td>22.2 ± 0.1</td>
</tr>
<tr>
<td>Heat of solidification (J/g)</td>
<td>49.8 ± 4.3</td>
<td>60.7 ± 3.3</td>
<td>65.9 ± 3.4</td>
</tr>
</tbody>
</table>

Table 5 : Decorative wood-based panels properties
Wood-based products such as MDF and HDF are materials with a low thermal conductivity. This can limit the thermal exchange and thus the PCM melting and solidification rate. In order to assess this thermal exchange, an additional experiment was achieved. Three panels containing PT23 were manufactured and characterized. The first panel was a standard wood-based panel as presented above. For the second and third panel, HDF was replaced by a 2 mm thick aluminum plate and by a standard 9.5 mm thick gypsum board, respectively. The panels were placed in the Fox FX 314, stabilized at 18°C and then the temperature was fixed at 26°C. The time required to melt the PCM with the HDF, the aluminum and the plasterboard were recorded and were respectively 3.6 h, 2.8 h and 4.8 h.

It is important to consider that the panels from the present study are designed to constitute the most inner layer of a wall. Therefore, the 5.5 mm HDF sheet (covered with 1 mm thick maple veneer) is the only layer separating the PCM from the interior air. In comparison with an implementation of PCMs behind a plasterboard, the thermal exchange could be higher for the wood-based panels, as our experiment suggests. A full scale-experiment is required to conclude about the efficiency of such panels as a thermal management solution.

Table 6: Comparison of wallboards properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting temperature (°C)</th>
<th>Solidifying temperature (°C)</th>
<th>Melting heat (J/g)</th>
<th>Reference</th>
<th>Measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capric-myristic acid / Expanded perlite (55/45 w%)</td>
<td>21.7</td>
<td>20.7</td>
<td>85.4</td>
<td>[39]</td>
<td>DSC</td>
</tr>
<tr>
<td>PEG (50 w%)/diatomite</td>
<td>27.7</td>
<td>32.2</td>
<td>87.1</td>
<td>[40]</td>
<td>DSC</td>
</tr>
<tr>
<td>Wood / RT27</td>
<td>26.2</td>
<td>-</td>
<td>20.6</td>
<td>[15]</td>
<td>DSC Mettler Toledo</td>
</tr>
<tr>
<td>Wood-based PT20</td>
<td>20.2</td>
<td>19.8</td>
<td>56.9</td>
<td>Present study</td>
<td>DHFMA Lasercomp FX314</td>
</tr>
<tr>
<td>Wood-based PT23</td>
<td>22.2</td>
<td>22.2</td>
<td>57.1</td>
<td>Present study</td>
<td>DHFMA Lasercomp FX314</td>
</tr>
<tr>
<td>Wood-based CA/LA</td>
<td>20.8</td>
<td>20.5</td>
<td>47.5</td>
<td>Present study</td>
<td>DHFMA Lasercomp FX314</td>
</tr>
</tbody>
</table>
3.3 Thermal cycling

Fusion, solidification temperatures and total heat storages of the panels, before and after cycling, are shown in Table 7.

<table>
<thead>
<tr>
<th>Panel filled with</th>
<th>Melting point (°C)</th>
<th>Total fusion heat over 3°C (J/g)</th>
<th>Solidifying point (°C)</th>
<th>Total solidification heat over 3°C (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA/LA</td>
<td>20.6</td>
<td>48.6</td>
<td>20.4</td>
<td>52.8</td>
</tr>
<tr>
<td>CA/LA after cycling</td>
<td>20.5</td>
<td>48.1</td>
<td>20.4</td>
<td>48.4</td>
</tr>
<tr>
<td>PT20</td>
<td>20.2</td>
<td>58.7</td>
<td>19.6</td>
<td>63.9</td>
</tr>
<tr>
<td>PT20 after cycling</td>
<td>20.1</td>
<td>60</td>
<td>20.4</td>
<td>60.3</td>
</tr>
<tr>
<td>PT23</td>
<td>22.1</td>
<td>54.1</td>
<td>22.2</td>
<td>63.7</td>
</tr>
<tr>
<td>PT23 after cycling</td>
<td>22.3</td>
<td>54.7</td>
<td>21.6</td>
<td>63.6</td>
</tr>
</tbody>
</table>

Thermal cycling did not seem to affect fusion temperatures. Solidification temperatures of Puretemp® products were affected. PT20 had a solidifying point 1.2 degrees higher, which is something positive, as its supercooling was reduced. For PT23, it was 0.6 lower. Explaining these shifts is complicated as Puretemp® mixtures composition is unknown. A comparison of the panel’s thermal behavior before and after aging can be seen in fig 5.
Except for the solidification shift, panels had overall the same thermal behavior before and after aging.

*Figure 5: Comparison between control and aged curves*

### 3.4 Comparison between DSC and DHFMA methods

Table 8 presents a comparison between DSC and DHFMA tests. Product PT20 was removed as its repeatability among tests wasn’t sufficient, as detailed above. The heat storage values were not compared because DHFMA tests are run on panels, while DSC tests are run on pure products. Thus, DHFMA measurements include the sensible heat of wood. Comparison will be done with the mixtures before aging.

**Table 8: Comparison of DSC and DHFMA panels results**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Test method</th>
<th>Melting point onset (°C)</th>
<th>Solidifying point onset (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA/LA</td>
<td>DSC</td>
<td>19.7 ± 0.1</td>
<td>23.5 ± 0.3</td>
</tr>
<tr>
<td>CA/LA</td>
<td>DHFMA</td>
<td>20.6 ± 0.1</td>
<td>20.5 ± 0.1</td>
</tr>
<tr>
<td>PT23</td>
<td>DSC</td>
<td>22.3 ± 0.2</td>
<td>25.6 ± 0.2</td>
</tr>
<tr>
<td>PT23</td>
<td>DHFMA</td>
<td>22.2 ± 0.2</td>
<td>22.2 ± 0.1</td>
</tr>
</tbody>
</table>

For product PT23, melting points were found almost identical with the two methods, with a 0.1°C difference. For CA/LA mixture, melting point was found 0.9°C higher with DHFMA test method. As DHFMA tests are driven according to a step-by-step method, the incertitude over the measure is dictated by the setpoints width. A shifted third experiment on the panels would have reduced this incertitude. It would also have enhanced the number of points available to determine the onset fusion temperature. Indeed, it is done by drawing a line at the maximum slope of the peak and precision is higher with a larger number of points. Beside these considerations, the DHFMA step-by-step method has the advantage to get rid of the thermal inertia of samples and surface effects that can affect the results with the DSC. [29]

In DSC tests, solidifying points were respectively found 3°C and 3.4°C higher for CA/LA and product PT23. DHFMA results are concordant with literature, as organic PCM’s usually show a little supercooling [35]. Reasons for the higher values with DSC tests were already discussed previously.
3.5 Moisture behavior

Deformation of panels at different steps are shown in fig 6.

Panels undergo cupping when submitted to humidity as shown fig 6b and 6d. They also tend to crown during the dry cycle as shown fig 6c.

The panels seem to have similar behaviors. However, amplitude measurements from Table 9 reveals a difference in behaviors between PCM and control panels.
Table 9: Amplitude of measure for PCM and control panels

<table>
<thead>
<tr>
<th>Control panels</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude Cycle 1 (mm)</td>
<td>0.513</td>
<td>0.67</td>
<td>0.5035</td>
<td>0.562</td>
</tr>
<tr>
<td>Amplitude Cycle 2 (mm)</td>
<td>0.666</td>
<td>0.644</td>
<td>1.30825</td>
<td>0.873</td>
</tr>
<tr>
<td>Amplitude Cycle 3 (mm)</td>
<td>0.669</td>
<td>0.65025</td>
<td>0.6195</td>
<td>0.646</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PCM panels</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude Cycle 1 (mm)</td>
<td>0.581</td>
<td>0.510</td>
<td>0.594</td>
<td>0.562</td>
</tr>
<tr>
<td>Amplitude Cycle 2 (mm)</td>
<td>1.391</td>
<td>1.538</td>
<td>1.383</td>
<td>1.437</td>
</tr>
<tr>
<td>Amplitude Cycle 3 (mm)</td>
<td>0.665</td>
<td>0.694</td>
<td>0.689</td>
<td>0.682</td>
</tr>
</tbody>
</table>

PCM panels seem to have more withdrawal during the dry cycle, as their amplitude of measure is higher. This could be explained by the fact that PCM panels are grooved and thus have less mechanical strength. They would resist less to the bending forced caused by the withdrawal. For an industrial use, this behavior should be carefully mastered to ensure that the wood-based PCM panels meet customer expectations.
4. Conclusions

Phase change materials can enhance buildings thermal mass and thus lead to energy savings. This study aimed to assess properties of bio-based PCM and of decorative wood-based panels made with those PCMs.

These experiments show that the wood-based interior panels have a suitable phase change temperature and latent heat storage to achieve thermal energy storage in buildings. They can embody a large amount of energy, as high as 57.1 J/g for a melting temperature of 22.2°C, which is comparable to existing PCM wallboards. Thermal melting temperature over aging of CA/LA mixture and Puretemp® products was found stable. Solidification temperatures of Puretemp® products was found a slightly unstable. The comparison between DSC and DHFMA tests on PCM products revealed small differences for melting temperature and higher differences for solidification temperature. Reasons for these shifts were discussed and impact of DSC calibration was highlighted. The results presented in this article enhance the global knowledge on PCM thermal testing.

Hygro-mechanical tests revealed that the panels filled with PCMs undergo to higher dimensional fluctuations during a dry cycle. In case of an integration in a building, mechanical stability of such panels should be controlled.

The results presented above suggests that such decorative wood-based panels loaded with bio-based PCM have a great potential for thermal energy storage. They could be added in existing buildings with further developments. However, in order to assess the efficiency of such panels as a thermal management solution for buildings, full-scale experiments are required.

Conflict of interests

The authors declare no conflict of interest.

Acknowledgments

The authors are grateful to Natural Sciences and Engineering Research Council of Canada for the financial support through its ICP and CRD programs (IRCPJ 461745-12 and RDCPJ 445200-12) as well as the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB).
Bibliography


