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RESEARCH ARTICLE

# Thermal performance and mold discoloration of thermally modified wood containing bio-based phase change material for heat storage

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## Abstract

The work presents the results of thermal performance and mold discoloration of thermally modified wood-based composites incorporating multicomponent fatty acids as a bio-based phase change materials (BPCM). Thermally modified Scots pine (TMP), beech (TMB), and spruce (TMS) sapwood were impregnated with a multicomponent mixture of linoleic acid and coconut oil fatty acids at a ratio of 20:80. Samples with different BPCM uptakes were analyzed in the temperature range typical for building indoor conditions. Leakage tests were conducted and revealed that the maximum leakage for all the samples is 3% to 5%. T-history and heat flowmeter methods were used to evaluate the thermal characteristic of the composites. The incorporation of BPCM into thermally modified woods (TMWs) resulted in significant thermal mass improvements, expressed by the ability of the composites to store excessive energy in terms of latent heat and keep the temperature constant for long time. The specific heat capacity of the TMWs was around 2 J/g K, which increased to 4 to 8 J/g K after impregnation with BPCM, depending on the impregnation uptake. Results showed also that TMB has higher thermal conductivity than TMP and TMS, while incorporating of BPCM into these materials resulted in even improved thermal conductivity. Results showed that the thermal conductivity of TMP increased after incorporation of BPCM from 0.06 W/m K to 0.1 and 0.14 W/m K for TMP/BPCM with 48% and 95% uptake respectively. Mold tests showed that BPCM encapsulated in TMWs is less susceptible to mold discoloration compared to untreated wood.

### KEYWORDS
bio-based PCMs, energy storage, mold discoloration, thermal properties, thermally modified wood

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# 1 | INTRODUCTION

Bio-based materials from renewable sources become an inevitable part of the future technologies for human living environment, in particular in building and construction applications. Therefore, use of timber and other wood-based materials has experienced growth during the last decade in single and multi-floor buildings, due to the high ratio of strength to density, thus bringing renewability, sustainability, and climate benefits.[1-5]

Due to its chemical composition and anatomical structure, wood is sensitive to moisture and a nutrient for the microorganisms.[6] In addition, wood's moderate specific heat capacity and low density predetermine its low thermal mass, which limits its ability to respond to the temperature fluctuation and energy intermittency in buildings.[7] Furthermore, many commercially used wood species (eg, spruce) posses low permeability making it difficult for applications where an impregnation is needed.

A common industrial approach to improve the dimensional stability and durability of wood is thermal modification, whereby the wood is heated up in the range of 180°C to 215°C for a defined period of time in a medium without oxygen.[8] As a result, hemicelluloses are thermally degraded while cellulose and lignin are modified to high-molecular structures to reduce the hygroscopicity and improve the dimensional stability of wood.

The thermal mass of wood can be improved by incorporation of phase change materials (PCMs) into its porous structure. Wood in various forms (fibers, flour, solid wood, veneer) is a cheap bio-container that can naturally be integrated with based phase change materials (BPCMs)[9] and used as a building material with heat storage function. The composite material of wood and BPCMs can be incorporated in the internal walls,[10] flooring[7] or in the façades of the buildings.[11] A series of recently published studies investigated the importance of BPCMs, mainly fatty acids and their eutectic mixtures, for different applications in construction and building sectors and reported a promising thermal and chemical properties with appropriate working temperature, latent heat, and chemical stability.[12-14]

Wood impregnated with PCMs can be used in internal and external joineries to enhance the thermal mass of the building, control temperature fluctuations, and improve the thermal comfort in residential buildings.[9] As energy savings become an inevitable part of modern building, synergy between BPCM and wood comprises various options, for example, wood flour,[15,16] wood fibers,[17] and surface treatment of solid wood and wood composites[18-20] to host the BPCMs. Wood-BPCM composites working at temperatures of 18°C to 25°C can absorb extra heat and release it when the temperature decreases under a given comfort value to ensure more efficiently use of heat energy.

Studies regarding wood/PCM composites are concentrating on wood flour, solid or delignified wood. Examples are fatty acids or their mixtures impregnated in wood flour[21,22] or paraffin blended with poplar wood flour and graphite[23] to achieve latent heat capacity of 26.8 J/g. Recently, delignified wood has been studied intensively, for example, an eutectic mixture of capric-palmitic acids impregnated into delignified wood[24] with a retention of 61.2% demonstrated no leakage, a phase transition temperature of 23.4°C and latent heat of 94.4 J/g with good thermal stability. Another study[25] used delignified wood as an encapsulating material for impregnation of PCM claiming increased pore volume compared to the initial material. However, the approach of using delignified wood is debatable since lignin, having best thermal conductivity of the three structural polymers in wood, has been extracted.

Solid wood of alder[26] with 29.9 wt% retention of paraffin and coated with polystyrene to prevent leakage of the PCMs showed a latent heat value of 20.62 J/g. Temiz et al.[27] studied Scots pine sapwood impregnated with a eutectic mixture of capric acid (CA) and stearic acid (SA). After thermal characterization of the material, it was concluded that the system wood/CA-SA can be used for indoor temperature regulation and energy saving in timber constructions. Solid wood as a container for BPCM is particularly suitable for flooring. Placed directly above the source of heat, the engineered wood-BPCM floor can undergo many heating/cooling phases and thus, ensures significant gain of latent heat. In a study, Mathis et al.[7] engineered a thin upper layer of wood flooring for absorbing and storing solar energy at a temperature of 30°C. Oak and sugar maple wood impregnated with a commercial microencapsulated BPCM (Nextek29) demonstrated a latent heat of 7.6 J/g for the composite with 77% improvement in thermal mass compared to the untreated wood.

The above research ideas still have to cope with the inherited disadvantages of wood namely, moderate heat capacity and low thermal mass and thus, low ability to absorb and store thermal energy, low thermal conductivity, dimensional instability and bio-degradability. The above features of wood are of importance when BPCM are impregnated in the wood structure for heat storage in buildings. An example is the gap in the knowledge about mold growth on the wood and wood composites containing organic PCM with no findings in the literatures. Eventual mold growth and release of mycotoxins can affect the human health[28] which proves the need and importance of material testing.

Although widely used for external claddings of buildings, thermally modified wood has not been studied with regard to its ability to encapsulate BPCMs for heat storage. The present study focuses on thermally modified solid wood of Scots pine, spruce (softwoods) and beech (hardwood) as a container for BPCMs. A special emphasis has been set on the impregnability and leachability of the thermally modified woods (TMWs) and susceptibility to mold discoloration. The aim of the study is to reveal the thermal characteristics of the thermally treated wood-BPCM composite by using T-history and heat flow meter method and to investigate the feasibility of the TMW for encapsulation of the BPCM for building applications.

## 2 | EXPERIMENTAL

### 2.1 | Materials

A BPCM composed of coconut oil fatty acids (CoFA) and linoleic acid (LA) mixed in a ratio of 80:20[29] was used through the study. TMW samples (thermo-vacuum modification at 210°C) of Scots pine (*Pinus sylvestris* L.) (TMP) sapwood, beech (*Fagus sylvatica* L.) (TMB) and spruce (*Picea abies* Karst.) (TMS) with dimensions of $9 \times 90 \times 90$ mm along the grain and without visible defects were used throughout the study.

### 2.2 | Methods

#### 2.2.1 | Incorporation of BPCM into TMWs and leaching test

The thermally modified samples were impregnated in an autoclave at temperature of 60°C to ensure melting and penetration of the BPCM in a vacuum-pressure process. Before the impregnation, the samples were conditioned

for 2 weeks at 23°C and 70% relative humidity. Two impregnation schedules were employed; high weight percentage gain (WPG) was achieved by immersing the samples in BPCM and applying a vacuum of 350 mbar for 10 min followed by 6 bar pressure for 1 h. Low WPG was achieved when a pre-pressure of 0.75 bars for 60 min was applied instead of vacuum step. Wood density, impregnation parameters and the average WPG are shown in Table 1.

The WPG was calculated as the difference between the initial ($m_i$) and final weight ($m_f$) of the wood sample and expressed in percent (Equation 1).[26]

$$\text{WPG} (\%) = \frac{(m_f - m_i)}{m_i} \times 100 \tag{1}$$

After the impregnation, the samples were conditioned in a cold room (10°C) for 3 weeks and the weight was recorded prior to the leaching tests. To assess the leaching rate of the BPCM, each impregnated sample was placed between two other untreated spruce and oak samples with identical dimensions. The 3-layer set was pressed by a mass of 1 kg and placed in a climate chamber at 35°C for 24 h. The cumulative leached amount of BPCM was calculated as a difference between the weight of the sample after 8, 16, and 24 h and related to the initial weight and expressed in percent (likewise Equation 1).

#### 2.2.2 | Thermal conductivity of TMWs/BPMC composites by heat flow meter method

The thermal conductivity of the samples was measured according to standards ASTM C1155-95 (2013) and ISO 9869-1:2014, known as heat flow meter method with some modifications.[30,31] The set-up is schematically depicted in Figure 1. An insulated box was used to minimize the heat loss from the samples' sides. In addition,

**TABLE 1** Wood density, impregnation parameters, and average weight percentage gain (WPG)

| Wood species | Density, kg/m³ | Duration and vacuum depth | Duration, pre-pressure | Pressure | Average WPG, % |
|---|---|---|---|---|---|
| TMP | 500 (88) | - | 60 min 0.75 bar | - | 48 (low) |
| | | 10 min 80% | - | 60 min 6 bar | 95 (high) |
| TMB | 643 (53) | 10 min 80% | - | 60 min 6 bar | 47 |
| TMS | 460 (57) | 10 min 80% | - | 60 min 6 bar | 62 |

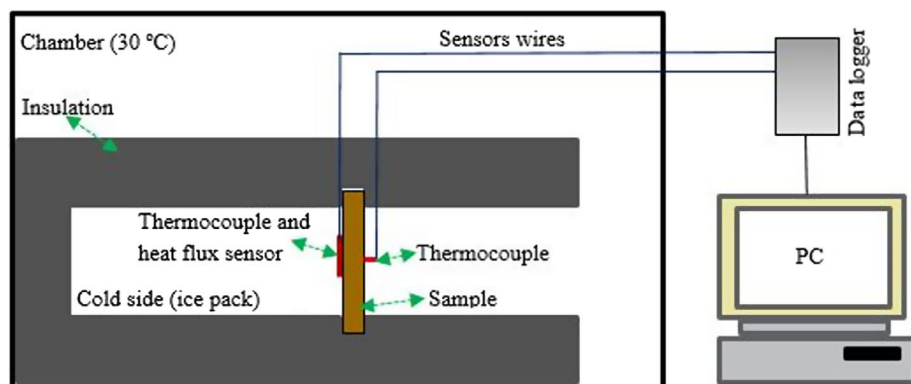*Note*: Number of tested samples per treatment were 4, SD in parenthesis.

**FIGURE 1** Schematic diagram of the designed rig for thermal conductivity

the samples were 10 times larger (90 mm) than the thickness (9 mm) to guarantee a low heat loss from other directions. Two thermocouples of K- and T-type were used to measure the temperature at the both surfaces of the sample. To avoid the effect of the surrounding environment on the measurements, the noncontact surface of the thermocouples were insulated. A heat flux meter type FHF03 supplied from Hukseflux, the Netherlands was used at the surface exposed to cold environment. Each measurement was run for 3 h to ensure a steady state process[32] and the experiment was repeated four times for reproducibility. After measuring the heat flux and the temperatures at both surfaces of the samples, the thermal conductivity was calculated by applying Fourier's law of thermal conduction[32]:

$$\lambda = \frac{q}{a} \cdot \frac{\Delta L}{\Delta T} \qquad (2)$$

where $\frac{q}{a}$ is the heat flux, $\Delta L$ is the thickness, and $\Delta T$ is temperature difference.

### 2.2.3 | T-history, specific heat capacity, and enthalpy

T-history method was used to measure thermal properties of several samples simultaneously[33-35] including melting/freezing point, latent heat of fusion, degree of super cooling and specific heat capacity. Unimpregnated TMWs sample, TMW impregnated with BPCM (TMWs/BPCM composite), and a copper (Cu) plate as reference with identical dimensions were tested simultaneously. The copper plate was used as main reference to obtain overall heat transfer coefficient ($u$). This parameter was then used to calculate the thermal properties of the other samples. The samples and reference were thermally insulated using 10 mm thickness ARMAFLEX insulation material. K-type thermocouples were used to record

**TABLE 2** Thermal and physical properties of references

|  | **Copper (SS 5011-04)** |
| --- | --- |
| Weight (g) | 657.6 |
| Dimension (mm) | 9 × 90 × 90 |
| Thermal conductivity (W/m K) | 395 |
| Specific heat capacity (J/g K) | 0.385 |

temperature changes over time for samples and references. The thermocouples were placed at the centerline and in the middle of the samples. For cold and hot ambient climate, two chambers were employed, the former used for cold ambient climate fixed at 10°C, while the latter chamber was used for hot ambient climate set at 35°C. The chamber's temperatures were recorded with two separate thermocouples. Thermal and physical properties of the reference is summarized in Table 2. Samples and reference were first preheated at 35°C, and then quickly transferred into the chamber at 10°C and the temperature profile was recorded. Once the equilibrium temperature was reached (ca. 3 h), the samples and the references were transferred back at 35°C and the temperature changes were recorded.

Energy balance for the reference was employed to obtain the overall heat transfer coefficient. Since the wooden samples and the metal reference have identical dimensions and insulation for uniform heat transfer conditions, the overall heat transfer coefficient ($u$) for both reference and wood samples were considered identical. The amount of heat transferred to/from samples in the chamber is expressed as follow[33]:

$$Q = uA\left(T(t)_n - T_\infty\right) \qquad (3)$$

where $Q$, $u$, $A$, $T(t)_n$, and $T_\infty$ are respectively the transferred heat, overall heat transfer coefficient, heat transfer area, sample temperature at each time point and ambient temperature inside oven/chamber.

The amount of heat stored/released from samples is:

$$Q = mC_p \frac{d(T_i - T(t)_n)}{dt} \quad (4)$$

where $m$, $C_p$, $T_i$, and $dt$ are respectively the mass of the samples, specific heat capacity, initial temperature, and time interval.

The amount of transferred energy to/from the samples is stored/released in/from the samples, then the energy balance is:

$$Q = -uA(T(t)_n - T_\infty) = mC_p \frac{d(T(t)_n - T_i)}{dt} \quad (5)$$

By rearrangement and integration, the temperature distribution for the reference and wood samples are obtained as:

$$\int_{T_i}^{T_n} \frac{d(T(t)_n - T_\infty)}{(T(t)_n - T_\infty)} = -\int_0^{t_n} \frac{uA}{mC_p} dt \quad (6)$$

After mathematical operation:

$$\ln\left[\frac{(T(t)_n - T_\infty)}{(T_i - T_\infty)}\right] = -\frac{uA}{mC_p} t_n \quad (7)$$

As the thermo-physical properties of the reference is known, the overall heat transfer coefficient ($u$) is calculated using energy balance for the reference:

$$uA = -\frac{\ln\left[\frac{(T(t)_n - T_\infty)}{(T_i - T_\infty)}\right]_{ref}}{t_n} m_{ref} C_{p,ref} \quad (8)$$

$uA$ is calculated by the energy balance for the reference according to Equation (8), and as heat transfer area and conditions around reference and wood samples are identical, $uA$ was calculated from the energy balance of the reference and used further to calculate $C_p$ for the wood samples. After substitution Equation (8) in Equation (7), $C_p$ of the samples is calculated as:

$$C_{p,samp} = \frac{\ln\left[\frac{(T(t)_n - T_\infty)}{(T_i - \infty)}\right]_{ref}}{\ln\left[\frac{(T(t)_n - T_\infty)}{(T_i - \infty)}\right]_{samp}} \frac{m_{ref}}{m_{samp}} C_{p,ref} \quad (9)$$

Enthalpy of the samples is obtained as[29]:

$$\Delta H = c_{p,samp}\left(T(t)_{n,samp} - T_{samp,i}\right) \quad (10)$$

where $\Delta H$ is enthalpy change from initial point to each time point $n$.

## 2.2.4 | Susceptibility of the materials to mold discoloration

The susceptibility of the TM wood/BPCM composites to mold growth and discoloration was tested according to the American Wood Protection Association Standard E24-06 (2015). Three mold fungi (*Aureobasidium pullulans* [d. By.] Arnaud, *Aspergillus niger* v. Tiegh and *Penicillium brevicompactum* Dierckx) were chosen and grown on 2.5% malt extract agar for 3 weeks. A mixed mold spore suspension was then prepared and inoculated on the sterilized soil in a plastic chamber. After inoculation, the chamber was incubated in a climate room at 20°C for 2 weeks. Afterwards, untreated, thermally modified and thermally modified impregnated samples with BPCM of Scots pine, spruce and beech were pit inside the chamber hanging approximately 5 cm above the soil. The climate in the chamber was maintained at 25°C and a relative humidity higher than 95%. After 2, 4, 6, and 8 weeks of exposure, the mold growth on the sample surfaces (90 × 90 mm) was classified by visual examination (Table 3) according to a scale from 0 (no visible growth) to 5 (very abundant growth, 100% coverage).

## 3 | RESULTS AND DISCUSSIONS

### 3.1 | Impregnation and leaching

Under the used impregnation schedules, WPG of 95% and 48% were targeted and achieved for the TMP samples, while a maximum of 47% WPG was possible for TMB (Table 1). This is due to the higher density of TMB than pine, which is in line with the findings in Nazari et al.[33] where the highest possible uptake for untreated beech was 43%. The effect of thermal modification on wood induces degradation of hemicelluloses, thus making the wood cell wall more porous and consequently easier to penetrate by liquids and gases. An example of the above effect is the improved permeability of TMS, where the refractory wood species spruce demonstrated 62% uptake of the BPCM.

Any BPCM is susceptible to leakage when integrated into buildings envelopes, which limits the application in buildings. Although suitable for encapsulation of BPCMs, the lignocellulose in any form can hardly prevent the leakage during exploitation.[36] The leaching test showed 4% and 3% loss of the BPCM for the TMP with 95% and

| Wood species and treatments | 2 weeks | 4 weeks | 6 weeks | 8 weeks |
|---|---|---|---|---|
| Scots pine | 2 | 3 | 4 | 4 |
| TMP | 0 | 0 | 1 | 1 |
| TMP/BPCM 48% | 1 | 1 | 2 | 2 |
| TMP/BPCM 95% | 1 | 2 | 3 | 4 |
| Spruce | 2 | 3 | 3 | 3 |
| TMS | 0 | 0 | 0 | 1 |
| TMS/BPCM 62% | 0 | 1 | 1 | 1 |
| Beech | 4 | 5 | 5 | 5 |
| TMB | 1 | 1 | 2 | 2 |
| TMB/BPCM 47% | 2 | 2 | 3 | 4 |

**TABLE 3** Ratings of mold growth and discoloration on untreated, thermally modified and thermally modified samples impregnated with BPCM (0 - no visible growth; 1 - covering up to 10% of surface; 2 - covering between 10% and 30%; 3 - covering between 30% and 70%; 4 - more than 70% of surface; 5 - 100% coverage)

48% WPG respectively. The values for the TMS and TMB were 4% and 5%. The study confirmed the positive effect of thermal modification on the permeability and restrain of leaching from wood were compared to untreated woods reported in Nazari et al.[33] It can be concluded that the cell wall has increased ability to accommodate and retain BPCM after thermal modification.

## 3.2 | Thermal conductivity measurement with heat flow meter

Thermal conductivity measurements showed that TMB has higher thermal conductivity compared to TMP and TMS. Prior to the impregnation of the BPCM, the thermal conductivity of the TMB, TMS, and TMP were 0.11, 0.07, and 0.06 W/m K respectively. The thermal conductivity varies between wood species and depends upon density and moisture content.[37] The thermal conductivity of untreated spruce and pine was reported to be in the range of 0.11 to 0.12 W/m K at 12% moisture content, while the value of untreated beech were in the range 0.18 to 0.21 W/m K.[37,38] In addition, the study reported a reduction in thermal conductivity both in radially and tangentially directions after thermal modification as a results of lower density and moisture content. This corroborates our results, which are in line with the reported data.[38]

Once impregnated with BPCM, all composites experienced improvement in thermal conductivity due to the PCM thermal conductivity (0.2 W/m K[29]) which is higher than that of TMWs. The results showed that TMP/BPCM composites with 48% and 95% impregnation uptake (after leaching) had thermal conductivity of 0.1 and 0.14 W/m K, respectively. A value of 0.12 W/m K was measured for TMS/BPCM with 62% BPCM uptake and 0.13 W/m K for TMB/BPCM with 47% uptake. The results showed that the increase of the BPCM uptake in wood increases the conductivity of the composite.
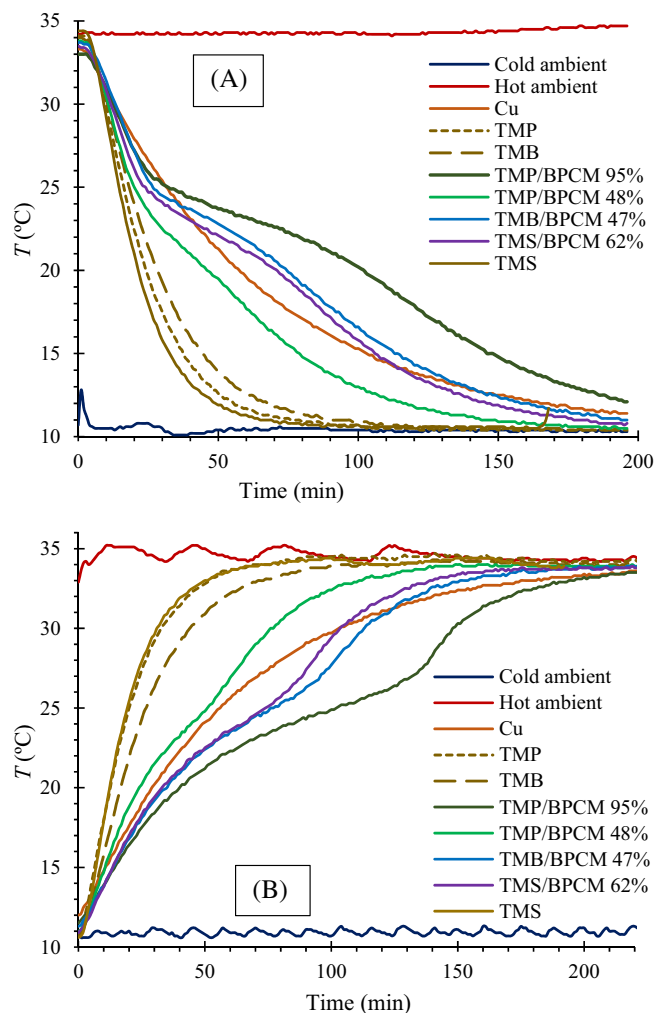


**FIGURE 2** T-history curves over cooling/heating cycle for (A) cooling and (B) heating

## 3.3 | Thermal analysis by T-history

Figure 2 shows the T-history profile for the samples and the reference (Cu) during the cooling (2a) and heating

process (2b). The measured ambient temperatures were constant throughout the experiments with ±0.8°C maximum deviation. Once placed in the climate chamber at 10°C, the samples and the reference's temperatures decrease gradually from the starting temperature at 35°C and continues to decease with the time until it reaches the chamber's ambient temperature (10°C). During the course of cooling cycles, a phase change transition was observed for all the TMW/BPCM composites at temperature around 24°C, and the BPCM inside the composites fully solidified at temperature around 22°C. In addition, the BPCM inside TMW/BPCM composites solidifies congruently.

During the cooling and heating processes (Figure 2), thermally modified samples without BPCM reached the equilibrium faster than the samples impregnated with BPCM. This is due to the increment in thermal mass (heat capacity, $mC_p$) of the composites compared to non-impregnated samples. The temperature profile of the materials in transient conduction condition (Equation 7) is a function of thermal mass of the materials $(mC_p)$. Increment in $(mC_p)$ leads to absorption and storage of more energy by the material during heating and release more energy during cooling process, resulting in delay for reaching the ambient temperature.

The results shows that the amount of BPCM inside the composites defines the thermal mass of the composite when the TMW has comparable density, which is the case for TMS and TMP samples. It can be seen that TMP with 95% uptake has the highest thermal mass, TMP with 48% uptake has the lowest, while TMS with 62% is in the middle. TMB has higher density compared to TMP and TMS leading to comparable thermal mass to TMS with 62% uptake, although TMB has lower uptake (47%).

Figure 3 illustrates the specific heat capacity for the tested samples calculated using Equation (9) during cooling and heating processes. Specific heat capacity of wood is temperature and moisture content dependent, and the wood species and density has no effect on specific heat capacity.[37] The measured specific heat capacity of TMWs without BPCM is around 2 J/g K which is in line with the reported data in the literature.[37] After impregnated with BPCM, considerable improvements of specific heat capacity were observed, moreover the BPCM retention seems to have an effect of the specific heat capacity although it is not much clear.

Figure 4 shows the calculated enthalpy for TMWs and TMWs/BPCM composites during cooling and heating processes. The TMWs before impregnation followed a linear trend showing that they only store and release energy in terms of sensible heat during heating and cooling processes respectively. While, TMWs/BPCM composites can absorb energy in terms of latent heat during the phase transition from solid to liquid (heating process), and release it during cooling process. In addition,
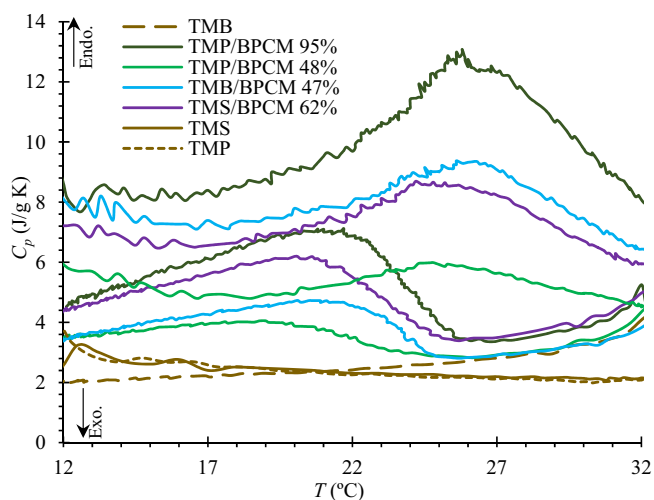


**FIGURE 3** Melting and freezing specific heat capacity for TMWs and TMWs/BPCM composites. BPCM, bio-based phase change materials; TMWs, thermally modified woods
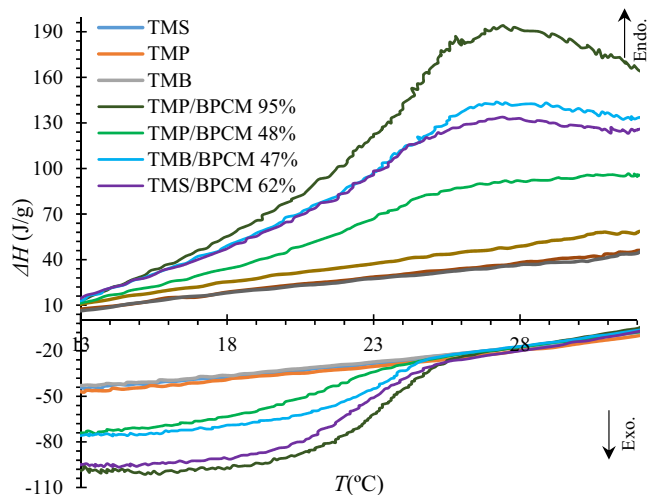


**FIGURE 4** Melting and freezing enthalpy for the samples

before and after phase transition they can absorb/release energy in terms of sensible heat.

The latent heat of pure BPCM is around 100 J/g,[29] and it reduces to ca. 70 J/g for TMP/BPCM composites of 95% WPG, and 30 J/g at 48% WPG, while this value for TMB/BPCM and TMS/BPCM at 47% and 62% WPG were ca. 45 J/g. The trend of enthalpy during cooling and heating process was found to be similar.

## 3.4 | Susceptibility to mold discoloration of the TMW and TMW/BPCM composites

Health problems related to mold growth and release of mycotoxins affect the occupants in buildings,[28] which

emphasizes the importance of material selection and living climate. The above is particularly important when BPCM are going to be introduced as heat storage solutions in buildings. The intention of the mold test was to study and compare the susceptibility of untreated samples, TMW and TMW/BPCM composites. The selected mold fungi are very common and grow well on pine and spruce.[39] The laboratory test was performed at optimal temperature and relative humidity for growth of the selected fungi. Another intention was to evaluate the laboratory test as an accelerated predictor of the discoloration process in practice. The average growth of the test fungi is shown in Table 3.

There is a significant difference between the mold growth on the untreated and TMW samples of the three wood species. Untreated beech is very susceptible to growth reaching a rate of 5 after 4 weeks of exposure while pine and spruce samples are similarly discolored to rates of 4 and 3 after 8 weeks of exposure. Beech, Scots pine sapwood and spruce samples were very susceptible to mold growth, which is probably related to the amount of available low-molecular sugars on the wood surface, for example, glucose, fructose and sucrose.[40,41] A similar susceptibility to mold growth on pine has been observed recently by Lie et al.[42] Compared to pine, the mold susceptibility of spruce varies between the studies, for example, spruce was found relatively more resistant by Viitanen and Ritschkoff[43] or demonstrated similar susceptibility to discoloring fungi as Scots pine sapwood.[42,44] The present study classifies spruce as somewhat better than pine regarding mold susceptibility.

Thermal modification improves significantly the resistance of the material to mold growth, which does not cover more than 10% to 20% of the sample surface (rates 1 or 2, Table 3). The finding is in line with the literature data, for example, .[42,45,46] TMW has always significantly lower equilibrium moisture content than the untreated wood[47]; the decreased moisture adsorption is a main limiting factor for the growth of fungi. Although less distinct on the TMW surface, the barely mold growth was clearly visible.

The mold discoloration susceptibility of the wood/BPCM composites of the three species is rated as better than the untreated samples, but worse than TMW. The growth rates (Table 3) are 2 and 4 for TMP and 4 for the TMB samples impregnated with BPCM. TMS wood impregnated with BPCM does not show difference to only TMS and is ranked as 1. Apparently, the uptake of BPCM in the TMP wood has some influence the growth rates being higher in a sample with higher BPCM uptake. Although the BPCMs are normally encapsulated in various forms and materials, they are always used in indoor environments and thus, the susceptibility of the composites to biological deterioration and degradation should always be considered. According to our knowledge, no studies investigating the long-term resistance of the BPCM materials to mold discoloration have been performed. The compounds of the BPCM in the present study, that is, the fatty acids, are utilized by the mold fungi as nutrients in a similar manner as the available carbohydrates on the sample surface. After the impregnation of wood with the BPCM, the surface is enriched and available to the mold growth. The BPCM can play some role as water-repellent formulation in the wood and it can postpone but hardly prevent the moisture adsorption. It has been demonstrated that the most common airborne fungal genera *Cladosporium* spp., *Penicillium* spp, *Aspergillus* spp. and non-sporulating molds[48,49] found in indoor environment are restricted by availability of moisture. Thus, the mold discoloration on TMW and wood/BPCM composites is lower compared to the unimpregnated wood; the later one being widely used for building.

# 4 | CONCLUSIONS

TMW including TMP, TMS, and TMB were impregnated with a multicomponent BPCM resulting in an enhanced thermal mass composites with potential use for building applications. The main findings of the work are summarized as follow:

- TMW can serve as container for BPCM; the chemical and morphological changes in wood caused by the thermal degradation of the main structural polymers ensure better permeability and better "hold" of the BPCM in wood compared to the untreated wood. The above is valid regardless the wood species.
- Thermal assessments showed that TMW/BPCM composites had higher thermal mass, it can absorb and release energy in the human comfort temperature range in terms of latent heat. Specific heat capacity of the composites is also higher than TMW without BPCM. The specific heat capacity of the TMWs were around 2 J/g K, which was increased 4 to 8 J/g K after incorporation of BPCM, depending on the BPCM uptake.
- Thermal conductivity of the TMW is less than untreated wood. After impregnation with BPCM, it was found that thermal conductivity of TMW/BPCM composites were higher than TMW. Results also showed that by increasing BPCM uptake, the thermal conductivity increases. This parameter was 0.06 W/m K for TMP and increased to 0.1 and 0.14 W/m K for TMP/BPCM with 48% and 95% uptake respectively. Results showed also that TMB has higher thermal

conductivity than TMP and TMS, while incorporation of BPCM into these materials resulted in even improved thermal conductivity.

- The mold susceptibility test showed that the appearance and growth of molds is related to critical levels of moisture and temperature. BPCM encapsulated in TMW is less susceptible to mold discoloration than the untreated wood. Having in mind the intensive use of wood in buildings, it can be concluded that wood/BPCM composites can serve equivalently or better than comparable wood elements without BPCM.

## NOMENCLATURE

$A$    Heat transfer area [m$^2$]
$c_p$   Specific heat [J/g K]
$H$    Enthalpy [J/g]
$L$    Thickness of the samples [m]
$m$    Mass of the samples [kg]
$Q$    Heat [W]
$q/a$   Heat flux [W/m$^2$]
$T$    Temperature [°C]
$t$    Time [s]
$u$    Overall heat transfer coefficient [W/m$^2$ K]

**Greek symbol**

$\lambda$    Thermal conductivity [W/m K]
$\Delta$    Difference
$\infty$    Ambient

**Subscripts**

$f$     Final
$i$     Initial
$n$     Time point
$ref$   Reference
$samp$  Sample

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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