

Phase change material impregnated wood for passive thermal management of timber buildings

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Summary

The Scots pine (*Pinus sylvestris* L.) sapwood was impregnated with the eutectic mixture of capric acid (CA) and stearic acid (SA) as phase change material (PCM) via vacuum process for passive thermoregulation in timber buildings. The hygroscopic properties, mechanical properties, thermal energy storage (TES) characteristics and lab-scale thermo-regulative performance of wood/CA-SA composite were evaluated. The produced composite from PCM was morphologically and physico-chemically characterized by SEM, FT-IR and XRD analysis. Thermal energy storage (TES) properties, cycling chemical/thermal reliability, and thermal degradation stability of the produced composite were determined by TG/DTA and DSC analysis. The hygroscopic tests revealed that the wood/CA-SA composite showed low water absorption (WA) and high anti-swelling efficiency (ASE) after 264 hours in water. Wood treatment with CA-SA increased the bending and compression strength of wood. TG/DTA data demonstrated that the wood/CA-SA composite left higher residue of 10.31% at 800°C than that of wood with 6.87%. The DSC measurements showed that the obtained wood/CA-SA composite had a good TES capacity of about 94 J/g at 23.94°C. The cycling DSC results confirmed the eutectic PCM in wood indicated high chemical stability and storage/release reliability even though it was run 600 times melt/freeze. According to thermal performance test, the wood/CA-SA composite has ability of storing excess heat in the environment and preventing the heat flow to the environment. It can be concluded that the fabricated wood/CA-SA composite can be used for indoor temperature regulation and energy saving in timber buildings.

KEYWORDS

Capric acid, eutectic mixture, PCM, stearic acid, thermal energy storage, timber buildings, wood

1 | INTRODUCTION

The rise in energy consumption as a result of increasing the industrial and urban activities due to population, welfare and technological developments are a major global concern. Global energy consumption is estimated to grow

by nearly 50% until 2050. Reducing energy consumption is becoming priority issue around the world. Besides depleting natural sources for generating energy, petroleum-based fuel causes global warming, climate change, and greenhouse gas.¹⁻⁴ In particular, carbon dioxide as an important air pollutant is largely originated

from fossil fuels and plays important constituents of total greenhouse gas in the world.^{4,5} Without any additional efforts to reduce greenhouse gas (GHG) by governments, greenhouse gas emissions is predicted to rise by 52% till 2050.^{4,6} It is expected to increase Earth's average surface temperature about 1.1°C to 6.4°C by end of 2100, causing irreversible impacts on environment and ecosystem and severe damage on human health.⁴ One third of greenhouse gas emissions and 40% of the energy consumption are produced from the building sector in worldwide. Therefore, buildings use huge amount of energy for day-lighting, cooling, and heating in their interior environments.⁷⁻⁹ In November 2018, The European Commission has already commitment to reduce at least 40% of GHG emissions below to 1990 levels while improving energy efficiency by 32.5%, and increasing the renewable energy sources to 32%.^{10,11} To achieve these targets, researchers, architects, and building engineers are focused on reducing the building energy consumption, carbon emissions, and using and storing renewable energy sources.^{7,9,12}

Solar energy provides clean energy, which is abundantly available for whole year. However, it can be used only during sunny days thus; energy storage system is needed for later usage. The latent heat storage (LHS) has been used in different applications due to providing higher energy storage density with a smaller temperature swing.³ Thermal energy storage (TES) method using with phase change materials (PCMs) has been growing interest due to decreasing heating, ventilation, and air conditioning times while it saves energy and reduces fossil fuel consumption and as well as pollutant emissions.¹³⁻¹⁵

PCMs are capable materials for absorbing and releasing large amounts of thermal energy in latent heat form via phase-changing process. PCMs offer improving the energy efficiency in building and reducing the fossil sourced-energy consumption.¹⁶⁻²⁰ PCMs are classified into inorganic, organic, and eutectic materials. Each PCM possesses different characteristics in term of their thermal behavior and latent heat storage.²¹⁻²⁶ Organic PCMs including fatty acids, fatty alcohols, PEGs, paraffins and their eutectic mixtures have been generally used for latent heat storage due to their high latent heat capacity, proper phase change temperature within wide range, non-corrosivity, non-toxicity, good thermally/chemically stability, low vapor pressure, very small volume change and mostly no super-cooling.^{16,27-32} PCMs can be integrated in building materials by using impregnation and encapsulation. Currently, the most of microencapsulated PCMs was integrated with several building elements for TES practices.^{13,23,28,33-35}

Wood is a popular building material. Beside of its renewability, wood also requires simple fabrication, relatively lighter weight, reusable, low carbon emissions (15 kg/m³), high carbon storage (250 kg/m³), and

environmentally compatible.^{36,37} Therefore, multi-storey wooden buildings around to world become popular in constructions during last decade. A sustainable and innovative solution would be thermal-powered storage technology as a flexible and reliable way to store heat by means of PCMs incorporated into lignocellulose matrix.³⁸ A few studies were concentrated on wood flour and modified wood/PCM composites. Jiang et al.³³ impregnated four kinds of fatty acid by wood flour (WF) in mass fraction of 50 wt%. The phase change transition temperature and latent heat of fusion of the prepared composites were found about in the range of about 40°C to 53°C and 88 to 103 J/g, respectively. Ma et al.³⁴ investigated the influence of chemical activation of poplar WF on the incorporation ratio and thermal properties of eutectic mixture of lauric acid and myristic acid. The activation process changed slightly the melting temperature and increased the latent heat of the composite PCM by 15% to 54.2%. Guo et al.³⁵ blended the paraffin with WF poplar (*Populus tomentosa* Carr.), high-density polyethylene, and graphite using a co-rotating twin-screw extruder. They measured the latent heat capacity of the composite PCM as 26.8 J/g. They also reported that the graphite addition was increased the thermal conductivity while decreased its flexural properties. Barreneche et al.³⁶ impregnated two types of paraffin into wood board (*Alnus glutinosa*), and then the composite was coated with polystyrene to avoid the leakage of the PCMs. They reported the optimum mass fraction and latent heat value of the composites as 29.9 wt% and 20.62 J/g. In some studies, delignified wood was preferred as supporting material for high impregnation of PCM because of its relatively improved pore volumes compared with non-lignified wood. Ma et al.³⁷ prepared two composite PCMs by incorporating capric-palmitic acid eutectic mixture with wood samples with/without delignified. They observed that the impregnation ratio was increased from 46.8 to 61.2 wt% while the latent heat capacity of the composite was boosted from 71.8 to 94.4 J/g after delignification treatment. Cheng et al.³⁸ developed delignified WF/myristyl alcohol composite and then mixed with urea-formaldehyde (UF) resin to produce composite board with desired shapes and sizes and satisfactory mechanical properties. The latent heat capacity of the composite containing 75 wt% PCM was measured as 166.5 J/g. Moreover, they also fabricated two composite boards by changing the amount of UF resin and reported that the flexural strength of the composite was increased by altering the mass fraction of the UF resin from 15 to 20 wt% and then declined when it was achieved to 30 wt%.

As understood from the above-summarized literature, the most of the studied has been intensified generally on

the TES properties of WF or delignified WF based-composite PCMs. As diverse from these researches, this work is aimed to investigate hydroscopic, mechanic, cycling thermal reliability, thermal degradation stability, and TES properties of a PCM impregnated solid wood besides its lab-scale thermal management performance. With this regard, until now there is no published study, which is about the development of a PCM incorporated Scots pine (*Pinus sylvestris* L.) and the evaluation of the produced composite as a thermo-regulator material for timber buildings. The capric acid-stearic acid (CA-SA) eutectic mixture was selected as a PCM because it has good cycling chemical and thermal stability, minor sub-cooling degree, low vapor pressure and chemically inert property; besides it is environmentally friendly bio-based PCMs which are produced from animal and vegetable fats and oils.^{39,40} The another important reason is that it has relatively high latent heat capacity (178 J/g) and very proper phase change temperature (24.7°C) for solar passive thermal controlling of buildings. Scots pine wood was preferred in this study due to widely available in most countries, easily manipulated into engineering timber products such as cross laminated timber and glulam and low cost and eco-friendly element for buildings. Fourier transform infrared (FT-IR), X-ray diffraction (XRD) analyses, and SEM were performed to characterize the chemical, crystalline structures and morphology of the PCM impregnated wood. The water absorption and anti-swelling efficiency of the PCM impregnated wood were estimated. Bending and compression tests of wood/CA-SA were studied. The TES properties and thermal degradation stability of the wood/CA-SA composite were determined by differential scanning calorimetry (DSC) and thermogravimetry (TG/DTA) techniques. The cycling chemical stability and TES reliability of the produced wood/CA-SA were studied. Furthermore, its lab-scale thermo-regulative performance was also evaluated.

2 | MATERIALS AND METHODS

2.1 | Materials

Scots pine (*Pinus sylvestris* L.) sapwood was used in this study. Capric acid (CA; purity $\geq 98.0\%$) and stearic acid (SA purity $\geq 97.0\%$) were purchased from Sigma-Aldrich Company. The CA with melting temperature range of 29°C to 32°C and SA with melting temperature range of 69°C to 72°C were used as PCMs in the preparation of the eutectic mixture. In preparation of the eutectic mixture of CA-SA (83:17 wt%), the procedure described in the literature¹⁸ was followed.

2.2 | PCM impregnation process

PCM impregnation process was carried out in the vacuum oven under 640 mmHg at 45°C for three hours. After impregnation stage, the samples were removed from liquid PCM and weighed. The retention of PCM into the wood was calculated according to ASTM D 1413 standard by using the following Equation⁴¹:

$$\text{Retention (kg/m}^3\text{)} = ([G \times C] / V) \times 10 \quad (1)$$

where, G is grams of treating solution absorbed by Scots pine wood, C is the concentration of PCM solution (which corresponds to 100%), and V is the volume of samples (cm³). The retention amount of CA-SA into the wood was calculated averagely as 447.5 \pm 16.20 kg/m³.

2.3 | Morphological and physico-chemical characterizations

The microphotographs of Scots pine wood and CA-SA impregnated wood were taken using a JEOL JSM-5900LV model SEM instrument. The chemical structure of eutectic CA-SA, wood, and the fabricated wood/CA-SA composite were examined by Infrared Spectrophotometer (Thermo Scientific Nicolet iS10, Nicolet Co.). The spectral data was taken in scanning range 4000 to 400 cm⁻¹ with 4 cm⁻¹ resolution. The crystalline structures of eutectic CA-SA, wood, and the fabricated wood/CA-SA composite were analyzed using a XRD instrument (Rigaku model, Japan) with Cu K α at 35 kV and 30 mA. The analyses were carried out in the diffraction angles range of 5° to 70° (2 θ) at a scan rate of 0.04°/min.

2.4 | Thermal characterization of PCM impregnated wood

Thermogravimetric (TG)/Differential thermal analysis (DTA) was carried out using simultaneous TG/DTA thermal analyzer (SDT Q600 TA Instrument). The samples (5-10 mg) were placed in platinum pan under nitrogen at a heating rate of 10°C/min over a temperature range of 30°C to 600°C. Differential scanning calorimetry (DSC) analyses were performed to determine the melting and solidification enthalpy values with phase change temperatures of the CA-SA eutectic mixture and wood/CA-SA composite. Analyses was carried out at heating/cooling rate of 3°C/min under nitrogen atmosphere by using Hitachi DSC 7020 model DSC instrument. The measurements were replicated for three times and the mean deviation value was determined as $\pm 0.13^\circ\text{C}$ and $\pm 1.24 \text{ J/g}$

for the melting and solidification temperatures and latent heat values of the samples.

2.5 | Hygroscopic tests

To determine water absorption (WA) and anti-swelling efficiency (ASE) as hygroscopic properties, control wood and wood/CA-SA composites with the dimensions of $20 \times 20 \times 10$ mm were cyclically submerged in deionized water. The water was replaced with fresh water after 3, 6, 24, 48 hours and then every 48 hours for a total of 264 hours. After each cycle, the mass and dimensions of each sample were recorded. The experiments were conducted at room temperature. The WA and ASE values were calculated according to Equations 2 and 3, respectively, after each water replacement,

$$WA (\%) = ([W_2 - W_1] / W_1) \times 100 \quad (2)$$

$$ASE (\%) = ([V_u - V_t] / V_u) \times 100 \quad (3)$$

where, W_1 and W_2 are the weight (g), of the wood specimens before and after the test, V_u and V_t are the volumetric swelling coefficient of wood and the PCM impregnated wood, respectively.

2.6 | Mechanical tests

In order to determine the effect of PCM impregnation on the mechanical properties of wood, three-point bending (modulus of elasticity (MOE) and modulus of rupture (MOR)), and compression strength parallel to grain (CSPG) were carried out for control wood and wood/CA-SA composites. Samples were conditioned in a chamber with 65% relative humidity and 22°C before the mechanical test. Bending test of wood/CA-SA composites with the dimensions of $5 \times 10 \times 100$ mm were determined according to DIN 52186 using a universal testing equipment (MTS Criterion 40).⁴² The crosshead speed was 1 mm/min.

The MOE (N/mm^2) and MOR (N/mm^2) were calculated according to Equations 4 and 5, respectively.

$$MOE (\text{N/mm}^2) = ((P \times L^3) / (4 \times f \times b \times h^3)) \quad (4)$$

$$MOR (\text{N/mm}^2) = ((3 \times F \times L) / (2 \times b \times h^2)) \quad (5)$$

where, P is the different of load, L is the span, f is the rate of bending, b is the width of the sample, h is the thickness of the sample, and F is the peak load.

The compression strength parallel to grain (CSPG, N/mm^2) of wood/CA-SA composite with the dimension of

$20 \times 20 \times 30$ mm was determined according to DIN 52185 in a universal testing equipment (MTS Criterion 40).⁴³ The compression strength was calculated according to Equation 6.

$$CSPG (\text{N/mm}^2) = F_{\max} / (a \times b) \quad (6)$$

where, F_{\max} is the max load (N), a and b are cross sectional area (mm).

2.7 | Thermal cycling and thermo-regulative performance tests of PCM impregnated wood

Thermal cycling test was applied to specify the chemical and thermal stability of the prepared samples by using a thermal cycler instrument (Prime model, Carl Roth GmbH +Co.KG, Karlsruhe, Germany). The prepared sample were subjected to accelerated melting/solidification process by heating and cooling for 600 times between 5°C and 40°C . To predict the cycling TES life of the prepared wood/CA-SA composite, the samples were subjected to DSC and FTIR analysis after this process, and the results were compared with the initial samples that were not subjected to the thermal cycling test. The mean deviation regarding the three times repeated-DSC measurements was found to be $\pm 0.16^\circ\text{C}$ for melting and solidification temperatures, and ± 1.68 J/g for latent heat values of the samples.

Lab-scale thermo-regulative performance test of the PCM impregnated wood was carried out by forming two cubic cells for control and test purpose as shown in Figure 1.

Five walls of these cubes were formed from polystyrene foam, while the top walls ($50 \times 50 \times 10$ mm) of the test and control cells were made of wood/CA-SA and untreated wood, respectively. A 250 W bulb was used as the heat source for heating the cubes. The bulb was settled at the same distance (65 cm) to both test and control cubes. The ambient environment was measured as averagely 17.1°C during the thermo-regulation test. During the heating and cooling periods, a temperature recorder was used to record the change in the temperature of the inner surfaces of the top walls of both cubes and the centers of the cubes, and the temperature differences between these two cubes were revealed.

3 | RESULTS AND DISCUSSION

3.1 | Morphology, chemical and crystalline structure analysis results

Figure 2A,B indicates the microphotographs of Scots pine wood and PCM impregnated wood.



FIGURE 1 Lab-scale cubic designs constructed for the estimation of thermo-regulative performance of the PCM impregnated wood [Colour figure can be viewed at wileyonlinelibrary.com]

It is clearly observed from Figure 2A that the pine wood has a typical surface morphology and porous structure. However, after impregnation, its surface morphology was considerably changed because tracheids were occupied by the CA-SA (Figure 2B). This means that the fatty acid components of the eutectic PCM were homogeneously fasten onto the cavities of the wood due to good compatibility. The microstructures also proved that the CA-SA was well impregnated by the porous pine wood and its seepage from the composite structure was prevented owing to the capillary and surface tension force as well as hydrogen-bond interaction.

The FT-IR spectral of the eutectic CA-SA, wood, and the fabricated wood/CA-SA composite is shown in Figure 3.

The FT-IR spectra of Scots pine wood showed several peaks at 3329 cm^{-1} for acetylenic group of alkyne stretching vibration, 2925 and 2850 cm^{-1} for saturated aliphatic group of methylene C—H, 1700 cm^{-1} for

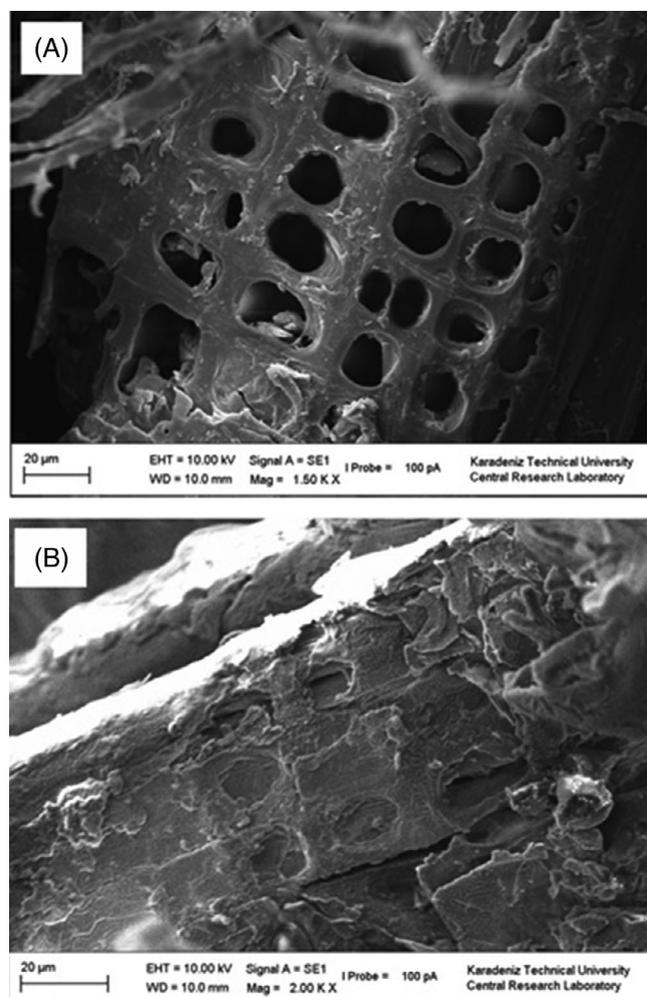


FIGURE 2 SEM microphotographs of Scots pine wood and CA-SA impregnated wood

carbonyl group of carboxylic acid, 1263 cm^{-1} for organic phosphates of P=O stretching vibration, 1032 cm^{-1} for organic siloxane or silicone (Si—O—Si) and 560 cm^{-1} for aliphatic C—I stretching vibration.⁴⁰ The peaks at 3329 , 2925 , and 1263 cm^{-1} are in agreement with the finding⁴⁴ which correspond to the structure of cellulose and lignin. After impregnation with CA-SA, wood/CA-SA composite showed combination of absorption peaks at 3331 cm^{-1} as O—H stretching, 2921 and 2845 cm^{-1} for methylene C—H stretching, 1703 cm^{-1} as carbonyl compound of carboxylic acid, 1421 cm^{-1} for simple inorganics of carbonate ion, 1293 cm^{-1} for organic phosphates (P=O stretching), 943 cm^{-1} for aromatic phosphates (P—O—C stretching), 691 cm^{-1} for simple inorganics of thiol or thioether and finally 561 cm^{-1} for aliphatic iodo compounds, C—I stretching. Detection of carbonyl compound and carbonate ion showed successful impregnation of CA-SA into the wood.

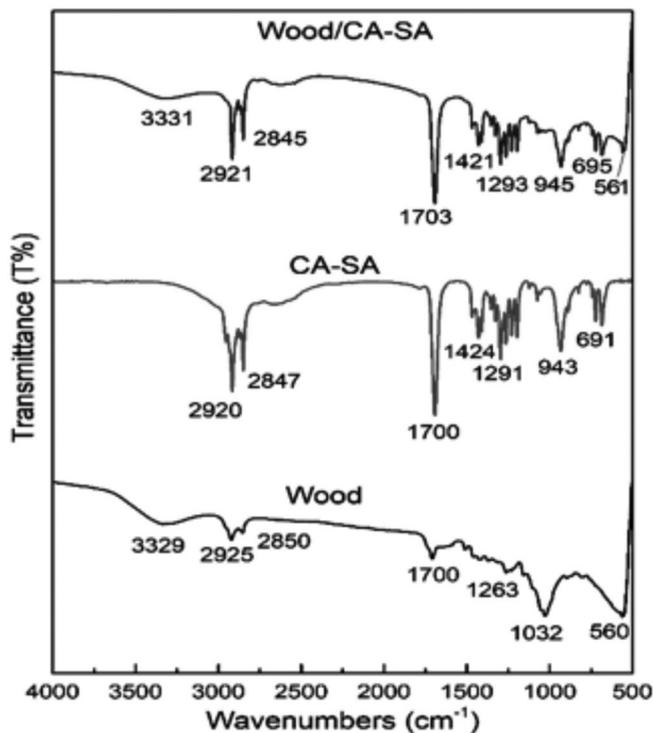


FIGURE 3 FT-IR spectra of the wood, CA-SA eutectic mixture, and wood/CA-SA composite

Figure 4 showed the XRD diffractogram of the eutectic CA-SA, wood, and the fabricated wood/CA-SA composite.

The CA-SA eutectic mixture exhibits three strong diffraction peaks located at 11.34° , 21.34° and 23.54° , respectively. The wood/CA-SA composite showed similar diffraction peaks, suggesting no changes in the crystal structure of eutectic mixture.⁴⁵ The crystallinity index of woody material can be calculated using peaks close to 18° and 22° which correspond to crystalline zone and amorphous zone of cellulosic materials, respectively⁴⁶ using the Equation 7;

$$\text{Crystallinity index, \%} = \frac{(I_{22} - I_{18})}{I_{22}} \times 100 \quad (7)$$

where, I_{22} and I_{18} indicate the peaks at 2θ value of about 22° and 18° , respectively. The change in crystallinity index can be ignored as there is only very slight increase from 9.0% to 9.5% between the wood and wood/CA-SA composite. This crystallinity index is in agreement with literature,⁴⁷ which reported the crystallinity index of the wood between 8° and 25° . No new diffraction peak was observed in the XRD pattern of wood/CA-SA composite, indicating that CA-SA impregnated wood do not undergo any chemical reaction with only physical combination.

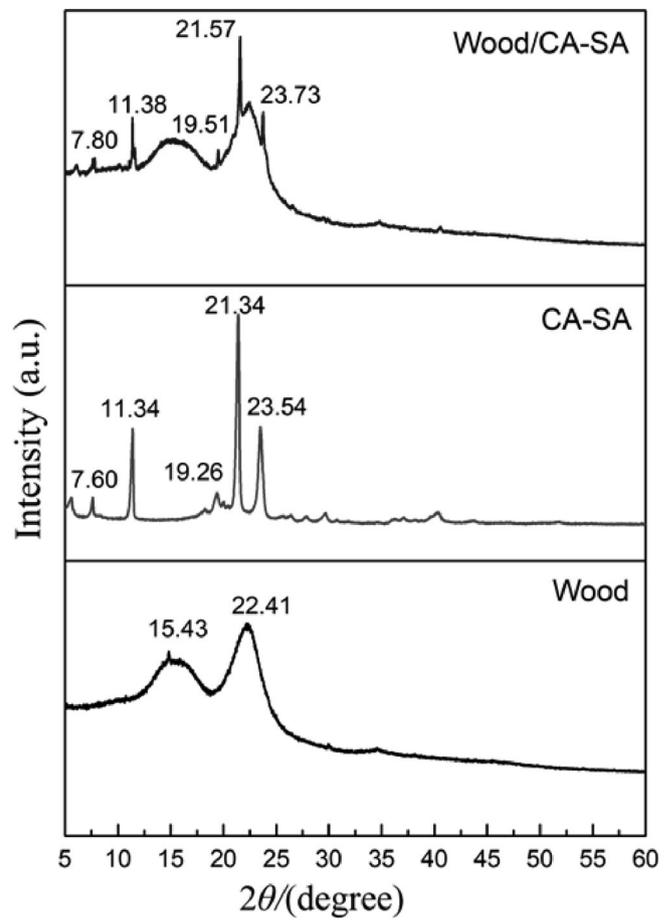


FIGURE 4 XRD diffractogram of the PCM, wood, and the wood/CA-SA composite

3.2 | Water absorption (WA) and anti-swelling efficiency (ASE)

The WA and ASE of the samples depending on the change in time were shown in Figure 5. The average retention of samples impregnated with PCM was $447.5 \pm 16.20 \text{ kg/m}^3$.

The WA of control wood ranged from 30.72% after 3 hours immersion in water to 80.32% after 264 hours of water exposure while wood/CA-SA composite showed from 4.03% of WA after 3 hours to 20.16% after 264 hours of water testing. The results showed that the PCM impregnation significantly reduced water uptake than that of control. It can be concluded that the wood impregnated with PCMs, containing fatty acids such as capric and stearic acids prevents water uptake into wood, providing hydrophobicity and thus keeps the wood moisture content below the fungi attack level. To increase hydrophobicity properties of PCMs, wood surface can be coated with varnishes, water repellents or polymers such polystyrene. It seems that PCMs, containing fatty acids can be used not only latent heat storage but also helps to

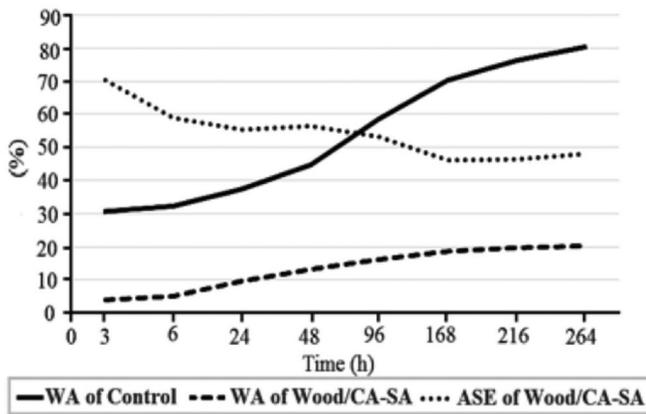


FIGURE 5 The changes in the WA and ASE values depending on the time

lowering wood moisture content below to fungi attack level in wooden multi-storey buildings. In addition, PCM impregnated wood showed relatively high ASE, indicating dimensional stability, from 70.21% after 3 hours in water to 48.02% after 264 hours exposure in water. It was reported in studies that wood treatment with oils such as linseed, tall, soybean oils prevent water uptake.^{48,49}

3.3 | Mechanical properties

The mechanical test results showed that the MOR of control and wood/CA-SA composite was 83.80 ± 6.7 N/mm² and 102.49 ± 5.3 N/mm², respectively, while the MOE of control and wood/CA-SA composite was 6270.36 ± 656.3 N/mm² and 7857.14 ± 788.0 N/mm², respectively. Average compression strength parallel to grain of control (untreated) and wood/CA-SA composite was 36.42 ± 2.54 MPa and 45.34 ± 1.75 MPa, respectively. It was found that the CA-SA impregnation increased the MOR (22.3%), MOE (25.3%) and CSPG (24.5%) of wood. The increase in mechanical properties can be attributed to the boosted density of wood due to filling wood cavities with CA-SA which was confirmed by SEM analysis. The strength of wood increases with the increase of wood density.⁵⁰

3.4 | TES properties of PCM-impregnated wood

The DSC analysis results for CA-SA eutectic mixture and wood/CA-SA composite are shown in Figure 6A.

The eutectic CA-SA mixture showed a melting temperature of 24.7°C, while wood/CA-SA composite had lowered the melting point to 23.94°C. It could be due to as follow:

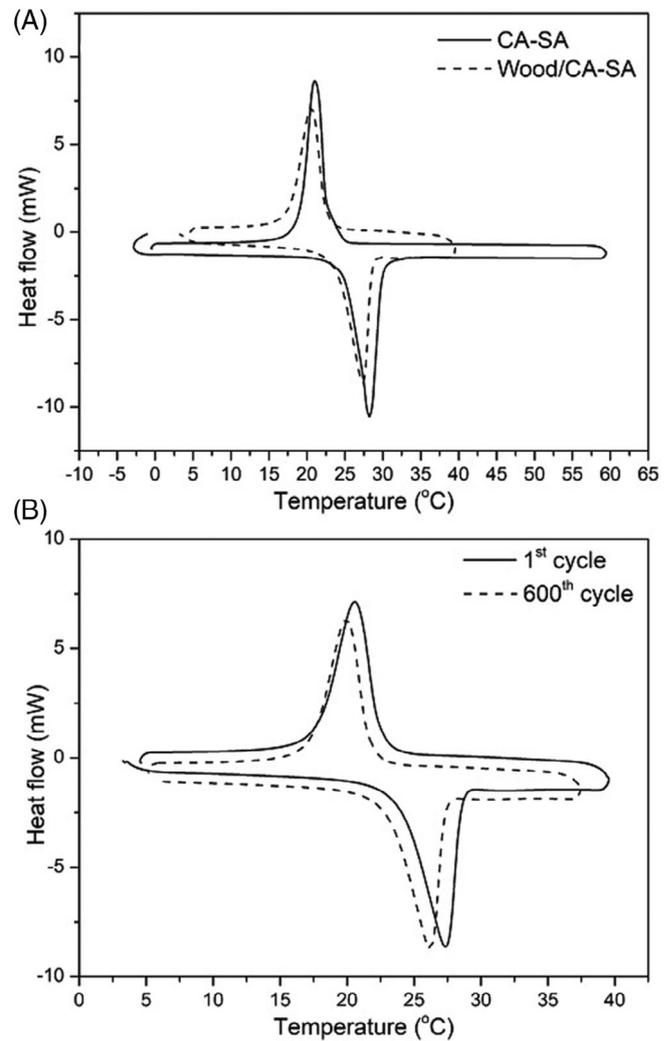


FIGURE 6 DSC heating and cooling scans of, A, CA-SA eutectic mixture and wood/CA-SA, B, of wood/CA-SA at 1st and 600th cycles

- The confinement of CA-SA into the pores of wood,
- Hydrogen bonding between the chains of fatty acids and lignin, cellulose and hemicellulose components of the wood,
- Effect of capillary forces between the CA-SA molecules and cell walls of the wood.

The similar results were obtained for different wood-based composite PCMs, WF/lauric acid-myristic acid³⁴ and wood/capric acid-palmitic acid.³⁷ On the other hand, the melting and solidification enthalpy values of Scots pine wood/CA-SA composite were measured as 94 and 82 J/g, respectively, while they were determined as 178 and 171 J/g for pure CA-SA eutectic mixture, respectively. Considering all DSC findings, CA-SA impregnated Scots pine sample is very suitable for the TES targets in building applications.

Thermal cycle test was performed to predict the cycling TES reliability of the wood/CA-SA composite. The cycling DSC thermograms of 1st and 600th cycled samples are shown in Figure 6B.

According to results, the thermograms obtained after thermal cycle were almost overlapping to before thermal cycle indicating the high thermal stability in wood. However, the melting and solidification points of CA-SA impregnated wood were lowered to 22.97°C and 22.05°C, respectively, at 600th cycle. As for the melting and solidification enthalpy values of the wood/CA-SA, they decreased to 92 and 81 J/g, respectively, after 600 cycles, meaning that almost no remarkable changes were occurred.

On the other hand, the cycling chemical stability of wood/CA-SA composite was examined by FTIR analysis in Figure 7. The FTIR spectrums after and before the thermal cycling test were compared with each other to observe any change of the characteristic peaks.

After 600 cycles, there was no any change in characteristic peaks of the sample, and any new peak was not detected. All findings revealed that wood/CA-SA composite can be used for long period.

3.5 | Thermal degradation stability of PCM-impregnated wood

Figure 8 showed the TG/DTA curves for wood, CA-SA eutectic mixture, and wood/CA-SA composite. Both original wood and wood/CA-SA demonstrated initial weight loss between 29°C and 100°C due to evaporation of water and volatile material.⁵¹

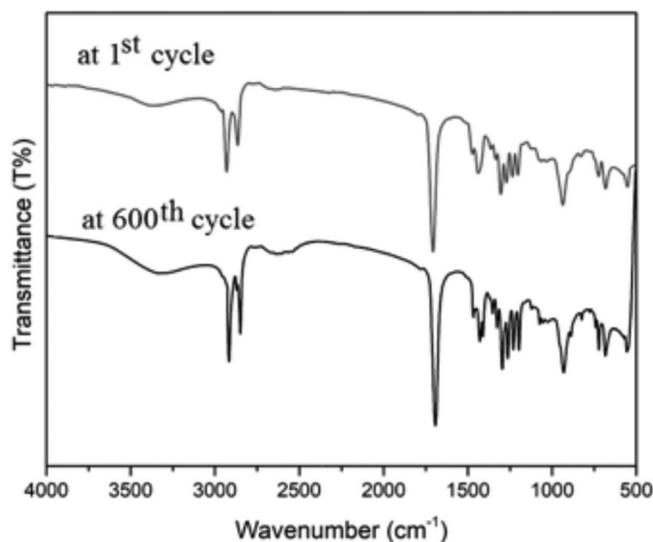


FIGURE 7 Comparison of FTIR results of the wood/CA-SA composite obtained at 1st and 600th thermal cycles

Faster weight loss for wood/CA-SA composite corresponds to the evaporation of PCM from the composite sample. Hemicellulose usually degrades between 100°C and 365°C while the cellulose decomposes at slightly higher temperature range, between 270°C and 400°C.⁵² Rapid thermal decomposition was observed at 203°C for the wood sample as shown by the DTA curve. The CA-SA indicated one-step thermal degradation between 123°C and 204°C. The impregnation of CA-SA helps to stabilize the composite sample at 200°C where no abrupt weight loss was observed at the respective temperature. Most rapid weight loss was happened at temperature 350°C for both wood and wood/CA-SA composite with the rate 30.2%/min and 35.0%/min, respectively. The wood/CA-SA composite left higher residue of 10.31% at 800°C, compared to the wood with 6.87%. This result indicates that wood/CA-SA composite had higher thermal stability of at extreme temperature compared to the wood.

3.6 | Lab-scale thermo-regulative performance

The temperature variations at inner surface and center of control and test tubes are given in Figure 9A,B.

According to the results, after heating for an equal period, the temperatures at the specified points of wood/CA-SA composite (test) were lower than the wood (control). In other words, overheating of the wood was delayed by the PCM content. For example, it took 910 seconds for wood/CA-SA composite to reach 30°C for internal surface temperatures while it took 2428 seconds for the wood/CA-SA composite. According to these results, it can be concluded that the ambient temperature overheating time can be delayed 166% with PCM.

The time to reach 28°C from the initial temperatures at the center of the control and wood/CA-SA composite was 1654 seconds and 2596 seconds, respectively, indicating 57% of delay. Another indicator of temperature regulation performance with PCM is to determine the average temperature values of both wood/CA-SA composite and control wood during the heating period. The average temperature of the control wood during the entire heating was 26.65°C, while this value was found to be 24.83°C for the wood/CA-SA composite. All these results can be explained with that PCM in the wood stores the excess heat from the environment and prevents the heat flow to indoor ambient.

According to cooling period results, the temperature of the wood/CA-SA composite at the specified point was higher than the control wood. In other word, overcooling

FIGURE 8 TG curves (main figure) and DTA curves (inset figure) for wood, CA-SA, and CA-SA/wood composite

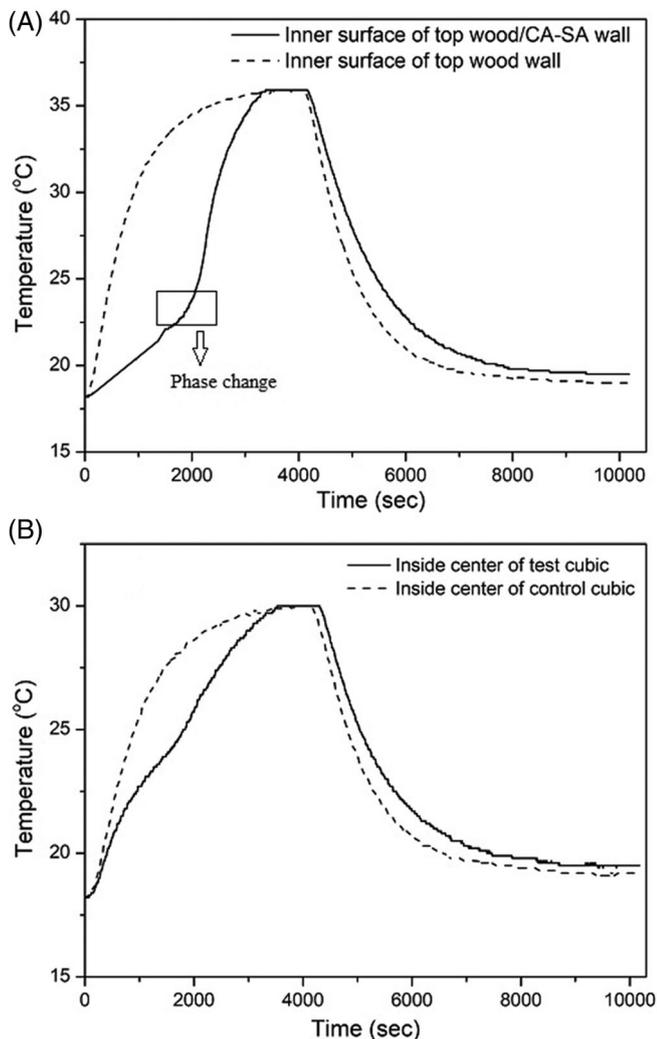
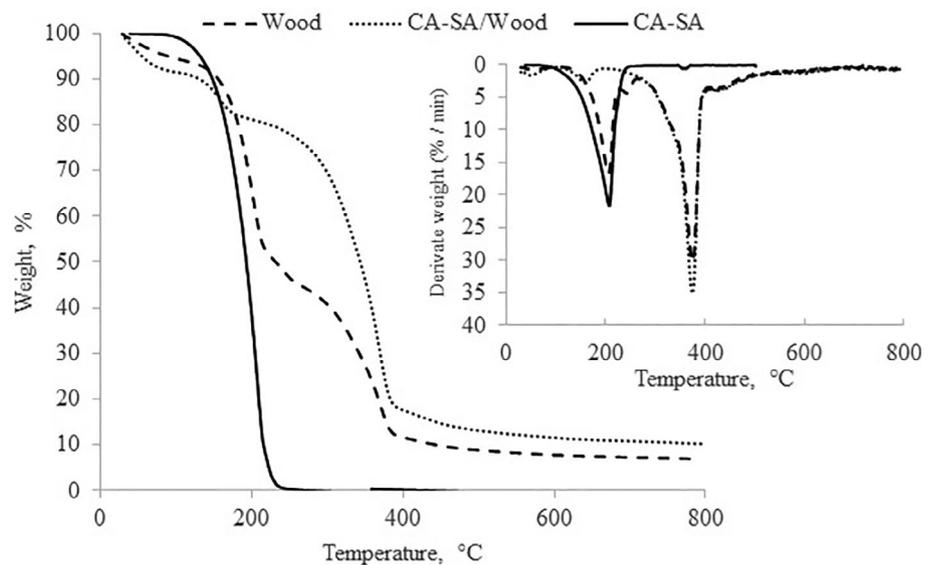


FIGURE 9 A, Temperature variations at inner surface location of top wall with/without PCM, B, at inner center locations of the test and control cubes

of wood is delayed with PCM. For example, decreasing the internal surface temperatures to 20°C for control wood was 6538 seconds while this time was found to be 7704 seconds for the wood/CA-SA composite; this means that the ambient temperature overcooling time will be delayed by PCM as approximately 18%. Regarding to center temperatures in cubes during to cooling period, the time to fall from the initial temperatures to 20°C lasted 6530 seconds for the control wood and 7602 seconds for wood/CA-SA composite, meaning 17% of delay. These results showed that the heat energy stored by the PCM released into the environment as the temperature decreases. Accordingly, the thermal performance test results show that PCM in wood stores excess heat in hot weather, preventing the rise of the ambient temperature and keep it at a comfortable level.

4 | CONCLUSIONS

This work was aimed to study the potential usage of Scots pine wood impregnated with CA-SA eutectic mixtures (83:17 wt%) of PCM as temperature regulative material in energy efficient-buildings. Retention of the eutectic PCM into Scots pine wood was $447.5 \pm 16.20 \text{ kg/m}^3$. The SEM, FTIR, and XRD result showed that the ingredients of the prepared composition were interacted with each other by only physically not chemically. The PCM impregnated wood noticeably reduced water uptake and increased the dimensional stability of wood. The MOR, MOE and CSPG values of PCM impregnated wood were higher about 22% to 25% than that of untreated wood. The DSC results of the prepared wood/CA-SA composite indicated good energy storage/release capacity with suitable phase

change temperatures for building TES applications. The TG/DTA measurements revealed that PCM impregnated wood left higher residue of 10.31% at 800°C than that of the untreated wood with 6.87%. Thermal cycling operation showed that the CA-SA eutectic mixture in wood was greatly stable in terms chemical structure and TES properties even after 600 cycles. The lab-scale performance experiment demonstrated that the PCM in the wood stores the excess heat in the environment and prevents the heat flow to the environment. In addition, the heat energy stored by the PCM is released into the environment as the temperature decreases. However, to estimate the actual thermo-regulative performance of the fabricated wood/CA-SA composite, further studies should be conducted in real-scale building designs.

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