

# Evaluation of Lauric-Myristic Acid as Phase Change Material in Thermally Modified Wood for Thermal Energy Storage

Gaye Kose Demirel \*

Thermally modified Scots pine samples were impregnated with lauric acid (LA) and myristic acid (MA) as phase change material (PCM) by vacuum process. The LA-MA mixture was prepared at a eutectic ratio of 66 to 34 wt%. Some properties of the wood samples such as hygroscopicity, mechanical, thermal energy storage (TES), and lab-scale thermo-regulative performance were investigated. Fourier transform infrared spectroscopy (FT-IR) was utilized to analyze the physicochemical characteristics of wood samples that underwent thermal treatment. The thermal degradation stability, cycling chemical/thermal reliability, and TES properties of the samples were assessed through TG (thermogravimetric analysis) and DSC (differential scanning calorimetry) analyses. The DSC results of thermally modified wood (TMW)/LA-MA samples showed good energy storage or release capacity with appropriate phase. These analyses also indicated that TMW samples infused with PCM exhibited reduced residue compared to the control samples. The experimental evaluation conducted on a small scale demonstrated that the PCM integrated within the wood effectively retains excess heat within the surrounding environment, thereby restricting heat dissipation. Moreover, the presence of PCM visibly decreased water absorption and enhanced the dimensional stability in wood. The impregnation with LA-MA improved mechanical properties of thermally modified wood despite the thermal modification that normally decreases mechanical properties.

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*Contact information:* Karadeniz Technical University, Department of Forest Industry Engineering, 61080, Trabzon, Turkey; \*Corresponding author: [gkose@ktu.edu.tr](mailto:gkose@ktu.edu.tr)

## INTRODUCTION

The growing world population requires more energy. Therefore, people need more sun and wind power. However, people also need a significant improvement in technologies that will lead to the use of clean energy sources such as zero-carbon fuels. The European Union (EU) had targeted to be carbon-free in the 1950's. In the near future, a diverse mix of energy solutions to support renewable energy that meets people's demands will possibly be the key solution, which might be the transition to clean energy. One of these solutions, lithium-ion batteries that are found in phones, electric cars, and computers are an example of a growing storage solution; even though they are mainly appropriate for short-term storage. Thus, the innovative challenge is to find reliable and remarkable ways to store renewable energy sources for days, months, or years. Research on this topic should also consider the seasonal changes, *e.g.*, short winter days, long periods of heat or cold for weeks or months (Hasan and Sayigh 1994; De *et al.* 2015; Najjar *et al.* 2019; Kirankumar

*et al.* 2020). Energy consumption in residential buildings is an energy-demanding sector that needs to be managed properly. Recent studies have reported that almost half of the energy generated in the EU is consumed in buildings. Thermal-powered storage technologies could be one of the innovative solutions. These technologies are a reliable solution to store heat with help of bio-based phase change materials (BPCM) located in a lignocellulose matrix (Farid *et al.* 2004; Benli 2013; Aditya *et al.* 2017; Aslani *et al.* 2019; Can 2023)

Matter, such as phase change materials (PCMs), can absorb or release relatively large amounts of thermal energy as latent heat during phase transitions. These substances show extraordinary properties, making them valuable in various applications related to thermal energy storage and temperature regulation. The PCMs can modify thermal insulation in buildings, reduce heating and cooling loads, and increase indoor comfort. They are employed in thermal energy storage systems to store excess energy during off-peak periods and release it when needed, helping to balance energy demand and reduce peak loads. The PCMs are employed in thermal management for electronic tools to absorb and dissipate heat generated during operation, restraining extra heating and prolonging lifespan of tools (Khudhair and Farid 2004; Chen *et al.* 2012). The PCMs are also employed in solar energy applications to store heat collected from solar panels and release it when sunlight is not present. This provides a continuous energy supply. Additionally, PCMs are placed in vehicles to regulate temperature in refrigerated trucks, electric vehicle battery cooling, and passenger comfort control. These applications stress the versatility and potential of PCMs in different industries, addressing energy efficiency, thermal management, and sustainable solutions. Current studies have explored new PCM formulations and applications to develop their performance and increase their usage (Haldorai *et al.* 2019; Ji *et al.* 2019; Liu *et al.* 2020; Wen *et al.* 2020; Nazari *et al.* 2022; Can *et al.* 2023).

As saturated fatty acids, LA and MA are commonly found in various natural sources that include animal and plant fats. Both LA and MA have a lack of double bonds in their carbon chains. It is known that saturated fats are usually solid at room temperature and increase the levels of low-density lipoprotein (LDL) cholesterol in the human body when excessively consumed. Therefore, in general, excessive consumption of these fats should be consciously avoided. In addition, LA and MA can also behave as PCMs because they undergo phase transitions at certain temperatures (Sari 2003; Keleş *et al.* 2005; Hekimoglu *et al.* 2021).

According to previous studies (Hasan and Sayigh 1994; Sari and Kaygusuz 2002), it has been suggested that LA and MA are suitable substances for heating purposes. Despite their higher melting temperatures, they can be adjusted to the desired level for passive solar space heating and agricultural heating applications by combining them in specific proportions, as proposed by Keleş *et al.* (2005). The eutectic composition is a specific mixture of two or more substances that has a different melting point among all possible compositions. In the case of lauric acid and myristic acid, their eutectic mixture has a suitable melting point for some applications, making it suitable for various applications, including thermal energy storage and temperature regulation.

Wood material has some inherent deficiencies such as dimensional instability, biodegradation when exposed to biotic (animal and plant pests), and abiotic (outdoor weather, temperature, chemicals, mechanical wear, *etc.*) conditions (Temiz *et al.* 2016). That is why it is important to impregnate wood. The purpose of impregnation is to protect the wood material against biotic and abiotic factors that damage the wood material and to

give it the longest possible period of use with appropriate chemicals for the service area. The use of biodegradable chemicals based on renewable materials in the impregnation process has gained more attention due to increasing environmental pressures (Richardson 2002). Numerous studies have been conducted to determine that the use of these chemicals provides resistance against biotic (fungus, insect, termite, *etc.*) pests and abiotic (outdoor weather conditions, *etc.*) conditions and significantly reduces the water intake of the wood. In these studies, natural oils, oil essences, waxes, silicones, natural resins, extractives, and resin acids were used (Bazyar *et al.* 2010; Tomak *et al.* 2011; Demirel *et al.* 2018; Temiz *et al.* 2008, 2010, 2013).

In recent years, due to the increase in environmental awareness, there have been increasing restrictions on the use of environmentally harmful impregnation materials in wood preservation. This has led to the development of new environmentally friendly methods that protect the wood material against biodegradation and increase its dimensional stability. One of these methods is wood modification. Wood modification means changing or improving its undesired properties. For this purpose, rot resistance and dimensional stability of wood are increased, water intake is reduced, and resistance to external weather conditions is increased. In the thermal modification method for wood, the aim is to heat the wood material in the specific temperature range where chemical reactions are accelerated. Thus, it provides a permanent change in the chemical structure of the polymer compounds in the cell wall. In this method, it is aimed to improve the wood properties without applying any chemicals to the wood (Hill 2006; Batista *et al.* 2015).

The combination of thermally modified wood (TMW) and impregnated PCM seems a clever approach to improve the thermal properties of wood products, providing energy-efficient solutions and increased comfort in various applications. Recent studies and improvements in this area allow for the exploration of new PCM formulations, impregnation techniques, and applications for increased thermal performance.

In this study, thermally treated Scots pine samples were impregnated with one of the phase change materials, a LA-MA eutectic mixture. The aim was to determine thermal energy storage properties of thermally modified wood to employ these wood materials in applications such as passive solar space heating and agricultural heating.

## EXPERIMENTAL

### Materials

Thermally modified Scotch pine samples were supplied from the Novawood company (Bolu, Turkey) thus, the samples were produced on an industrial scale with a closed (pressurized) hygrothermal system. In the thermal wood modification process, Scotch pine samples are heated for 2 h at the temperature of 212 °C. After heat treatment, the cooling is applied to the wood materials. The cooling consists of two steps which are cooling and conditioning. The first step lasts 11 h, and wood materials are cooled to 120 °C. Then, the second step lasts 6 h. When the temperature is reduced to 60 °C, the wood materials are taken from the boiler, which means the heating procedure is finalized.

LA (purity  $\geq 98.0\%$ ) and MA (purity  $\geq 98.0\%$ ) were obtained from Sigma-Aldrich (St. Louis, USA). The LA (melting point of 42.6 °C) and MA (melting point of 52.2 °C) were used as PCMs. The mixture of LA and MA (LA-MA) was prepared at a eutectic ratio of 66 to 34 wt%. This process was conducted considering the study of Keles *et al.* (2005).

### Impregnation Process of PCM Eutectic Mixture

TMW samples were impregnated with the LA-MA in the vacuum oven at 0.08 Mbar at 45 °C for 4 h. After impregnation, the samples were taken out from liquid and weighed. The weight percentage gain (WPG) was calculated using Eq. 1,

$$WPG (\%) = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

where  $W_2$  is the weight after impregnation (gr), and  $W_1$  is the weight before impregnation (gr). The WPG was achieved at 65% for WA test, 26% for thermal performance test, and 35% for mechanical tests samples.

### Fourier-transform Infrared, Differential Scanning Calorimetry, and Thermogravimetric Analyses

To determine the chemical compositions and examine the physicochemical interactions between the components, Fourier-transform infrared (FTIR) analyses were conducted using a Perkin Elmer Frontier Model instrument from the USA (Waltham, MA). Spectra were recorded at a resolution of 4  $\text{cm}^{-1}$ , covering the range of 4000 to 500  $\text{cm}^{-1}$ .

Differential scanning calorimetry (DSC) was utilized to determine the melting and solidification enthalpy values of the LA-MA eutectic mixture and TMW/LA-MA samples, which have phase change temperatures. The DSC analysis was performed using a Hitachi DSC 7020 instrument (Delhi, IN). The measurements were carried out under a nitrogen atmosphere, with a heating/cooling rate of 3 °C/min. The experiments were repeated three times, and the mean deviation values for the melting and solidification temperatures, as well as the latent heat values of the samples, were determined as  $\pm 0.13$  °C and  $\pm 1.24$  J/g, respectively.

A thermogravimetric analyzer (SDT Q600 TA Instrument; Waters, New Castle, DE, USA) was used in determining the thermal stability of the samples. The samples, weighing between 5 to 10 mg, were placed in a platinum pan under a nitrogen atmosphere. The heating rate was set at 10 °C/min, and the temperature range extended from 30 to 600 °C.

### Thermal Cycling and Thermo-Regulative Performance Tests

To assess the chemical and thermal stabilities of the prepared samples, a thermal cycling test was performed with the help of a thermal cycler (Prime model, Carl Roth GmbH+Co.KG, Karlsruhe, Germany). The samples underwent an accelerated melting and solidification process through 600 cycles of heating and cooling within the temperature range of 5 and 40 °C.

A thermo-regulative performance test on the PCM impregnated samples was conducted, as shown in Fig. 1, with two cubic cells.

A total of five walls composed of polystyrene foam were fabricated for these cubes, while the top walls ( $50 \times 50 \times 10 \text{ mm}^3$ ) of the test and control cells were produced from TMW/LA-MA and untreated wood, respectively. In the purpose of heating the cubes, a 250 W bulb was employed. The bulb was located at the same distance, which is 65 cm, to both test and control cubes. During the thermoregulation test, the environment was measured as on average 18.2 °C. Throughout the heating and cooling cycles, a temperature recorder was employed to record the temperature variations on the inner surfaces of the top walls and at both cubes' centers.



**Fig. 1.** Lab-scale cubic designs for predicting of thermo-regulative performance of the PCM impregnated wood

### Water Absorption and Anti-Swelling Efficiency

Tests of the water absorption (WA) and anti-swelling efficiency (ASE) were conducted following the standard method AWP A E4 (2003) established by the American Wood Preservers Association. The wood samples, with dimensions of  $20 \times 20 \times 10 \text{ mm}^3$  (thickness  $\times$  radial  $\times$  longitudinal length), were first conditioned to a moisture content of 12% prior to testing. Subsequently, both the treated and untreated samples were immersed in beakers containing deionized water. The water in the beakers was replaced at intervals of 3, 6, 24, 48 h, and then every 2 days, for a total of 14 days. After each time interval, the weights and dimensions of the samples were measured and recorded. After each water replacement, Eqs. 2 and 3 were used to calculate the WA and ASE,

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

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

where  $W_1$  and  $W_2$  are the wood sample weights (g) before and after test, and  $V_u$  and  $V_t$  are the volumetric swelling coefficients of untreated and treated wood, respectively.

### Mechanical Tests

To assess the impact of PCM on the mechanical properties of wood, three-point bending tests were performed on both control wood and TMW/LA-MA samples, measuring the modulus of elasticity (MOE) and modulus of rupture (MOR). Samples were chambered under the conditions of 65% relative humidity and 22 °C temperature before the bending test for two weeks. The dimensions of test samples were  $5 \times 10 \times 100 \text{ mm}^3$  based on DIN 52186 (1978) using a universal testing equipment (MTS Criterion 40, MTS Systems Corporation, Eden Prairie, USA). The loading speed was arranged as 1.0 mm/min. The MOE ( $\text{N/mm}^2$ ) and MOR ( $\text{N/mm}^2$ ) were calculated with Eqs. 4 and 5, respectively,

$$MOE = ((P \times L^3) / (4 \times f \times b \times h^3)) \quad (4)$$

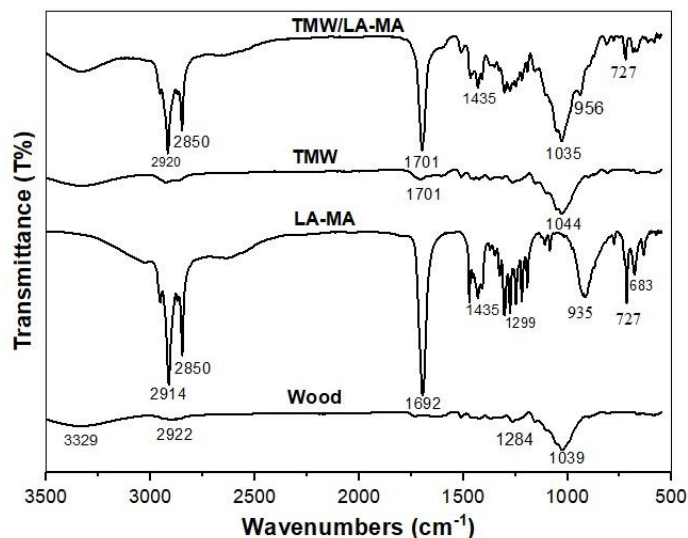
$$MOR = ((3 \times F \times L) / (2 \times b \times h^2)) \quad (5)$$

where  $P$  is the difference of load (N),  $L$  is the distance (mm),  $f$  is the bending rate,  $b$  is the sample width (mm),  $h$  is the sample thickness (mm), and  $F$  is the peak load (N).

## RESULTS AND DISCUSSION

### FTIR Results

The FTIR spectra of TMW, TMW/LA-MA, LA-MA, and wood samples are shown in Fig. 2.



**Fig. 2.** FT-IR spectra of the wood, TMW, LA-MA, and TMW/LA-MA

The FT-IR spectra of the LA-MA mixture could be easily observed in the impregnated specimens. As the amount of PCM in the wood increased, the absorbance peaks of the fatty acid in the modified wood specimens reached higher intensities, as shown in Fig. 2. Determination of the absorptions of LA-MA in impregnated samples showed the successful wood impregnation but there were no new bonds formed between the fatty acid and the wood matrix. As already stated in previous studies, only physical interaction between wood and fatty acids can be concluded according to the FT-IR analysis (Liang *et al.* 2018; Temiz *et al.* 2020).

The peaks observed at 3329, 2922, and 1299  $\text{cm}^{-1}$  are characteristic of the cellulose and lignin structures. After impregnation with LA-MA, the TMW/LA-MA samples showed a combination of absorbance peaks at 3329  $\text{cm}^{-1}$  that can be attributed to O–H stretching, 2920 and 2850  $\text{cm}^{-1}$  for methylene C–H stretching, 1701  $\text{cm}^{-1}$  for the carbonyl compound of carboxylic acid, 1435  $\text{cm}^{-1}$  for simple inorganics of carbonate ion, 1299  $\text{cm}^{-1}$  for organic phosphates (P–O stretching), 935  $\text{cm}^{-1}$  for aromatic phosphates (P–O–C stretching), and 683  $\text{cm}^{-1}$  for simple inorganics of thiol or thioether, as mentioned in previous studies (Song *et al.* 2014; Sari *et al.* 2020). Determining of carbonyl compound and carbonate ion contents indicated successful impregnation of LA-MA into the wood. The band located at 727  $\text{cm}^{-1}$  stands for –CH bond vibrations for the bending. The FTIR spectrum of LA-MA displayed similar characteristic peaks to the FTIR spectra of capric acid used in a different study (Sari *et al.* 2020).

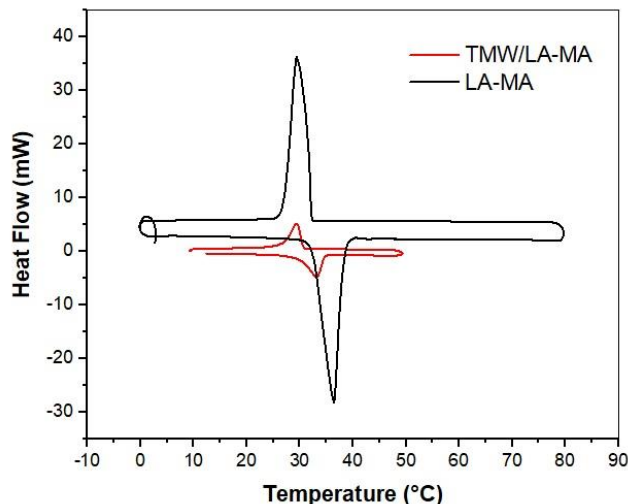
The IR spectrum of a PCM can put forward some valuable information about its chemical structure and properties, which are beneficial in identifying and characterizing PCMs. Furthermore, PCM can modify and potentially enhance the physical attributes of wood, including its dimensional stability. Generally, the chemical structure of PCMs is observable in wood samples. Notably, peaks at 2852  $\text{cm}^{-1}$ , 2922  $\text{cm}^{-1}$ , and 2958  $\text{cm}^{-1}$ , which

are indicative of PCMs, were also evident in the wood samples. Additionally, the characteristic PCM peak at  $720\text{ cm}^{-1}$  was observed at  $727\text{ cm}^{-1}$  in the wood samples.

### DSC Results

The DSC thermograms for the LA-MA and TMW/LA-MA are shown in Fig. 3. The DSC analysis was also employed to search the material's thermal activity. Thermal properties of the LA-MA and TMW/LA-MA were analyzed by DSC measurement, and the specific experimental data are summarized in Table 1.

The melting temperatures of the TMW/LA-MA, and LA-MA samples were  $33.11\text{ }^{\circ}\text{C}$ , and  $36.3\text{ }^{\circ}\text{C}$ , respectively. The melting temperatures of the TMW/LA-MA remained lower than that of the LA-MA. Latent heat of the LA-MA ( $177\text{ J/g}$ ) was much higher than that of the TMW/LA-MA ( $54.4\text{ J/g}$ ). Hydrogen bonds between the wood and PA were well formed, and therefore the cell and vessel cavities were unhindered; thus, the permeability was enhanced. The solidification temperatures of the TMW/LA-MA and LA-MA were  $30.8\text{ }^{\circ}\text{C}$  and  $32.4\text{ }^{\circ}\text{C}$ , respectively.



**Fig. 3.** DSC thermograms of LA-MA and TMW/LA-MA

**Table 1.** DSC Values of the LA-MA and TMW/LA-MA

	Melting		Solidifying	
	Peak Temperature ( $^{\circ}\text{C}$ )	Latent Heat (J/g)	Peak Temperature ( $^{\circ}\text{C}$ )	Latent Heat (J/g)
TMW/LA-MA	33.11	54.4	30.83	48.9
LA-MA	36.3	177	32.4	172

The eutectic LA-MA mixture exhibited a melting temperature at  $36.3\text{ }^{\circ}\text{C}$ , while TMW/LA-MA had a lower melting point of  $33.1\text{ }^{\circ}\text{C}$ . The possible factors contributing to the observed conditions include the encapsulation of LA-MA within the wood pores, hydrogen bonding interactions between fatty acid chains and the wood's lignin, cellulose, and hemicellulose components, as well as the influence of capillary forces between LA-MA molecules and the cell walls of the wood (Temiz *et al.* 2020).

The LA-MA eutectic mixture exhibited melting and solidification enthalpy values of  $177$  and  $172\text{ J/g}$ , respectively. The LA-MA mixture used for the production of innovative

form-stable materials becomes highly suitable with these thermal properties. These results are consistent with previous findings (Hekimoglu *et al.* 2021)

The latent heat of fusion for LA-MA was measured as 177 J/g (Nazari *et al.* 2021), but it was decreased to 54.4 J/g after being impregnated into wood. Similar behavior was reported (Ma *et al.* 2018; Yang *et al.* 2018a) when PCM was impregnated into wood.

## TGA Results

The weight loss was measured as a function of time and temperature in the TGA, as indicated in Fig 4. Table 2 lists the temperatures at which weight losses (at 10, 30, 50, and 75%) were produced and the amount of residue obtained after thermal degradation.

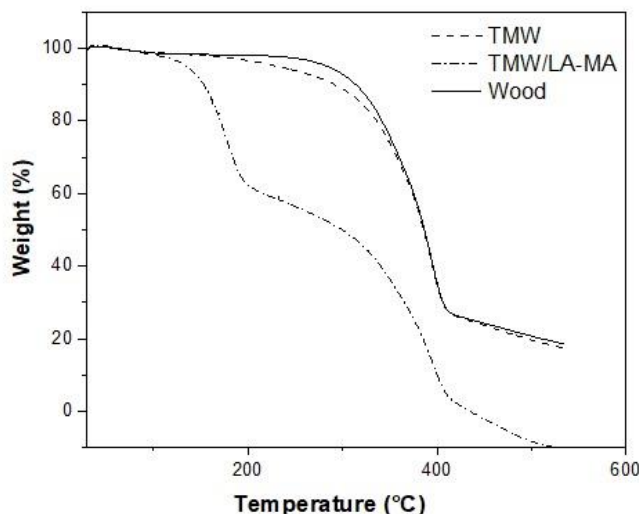


Fig. 4. TGA curves of the TMW, TMW/LA-MA, and wood samples

Wood with a sigmoidal shape, as shown in Fig. 4, indicates a single mechanism of degradation, with negligible weight loss below 290 °C, which corresponds to good thermal stability. Above 290 °C, the polymer begins to thermally decompose, until full degradation occurs at around 500 °C. The thermally treated wood with LA-MA (TMW/LA-MA) underwent material loss and degradation of epoxy (EP) component. The initial stage of thermal decomposition occurred between 150 and 200 °C, resulting in a weight loss of approximately 40% due to the breakdown of ester groups. The minor mass loss observed below 100 °C can be attributed to the evaporation of residual moisture and other solvents utilized during the manufacturing of the composite. The first stage commenced at around 100 °C and extended up to 210 °C, leading to a weight loss of 4%. The second stage primarily involved the degradation of the EP component, starting at approximately 210 °C and continuing up to 400 °C. At that point nearly all the EP was degraded, causing a weight loss of 33%. The final stage represents the degradation of the polymer, sawdust, and fibers constituting the composites, occurring from around 400 to 550 °C, leaving behind 10% residue. These results demonstrate that the materials, particularly the composite, exhibit thermal stability within the anticipated working temperature range, with degradation initiating at 200 °C.

The initial decrease in temperature, up to around 100 °C, can be attributed to the evaporation of moisture and volatile substances present in the wood (Sulaiman *et al.* 2016).



The subsequent phase may correspond to the degradation of the overall wood polymer structure (Amini *et al.* 2019). Cellulose degradation occurs within the temperature range of 200 to 400 °C (Sulaiman *et al.* 2016). Lignin degradation occurs at elevated temperatures but takes a longer period (Boon *et al.* 2017; Holy *et al.* 2022).

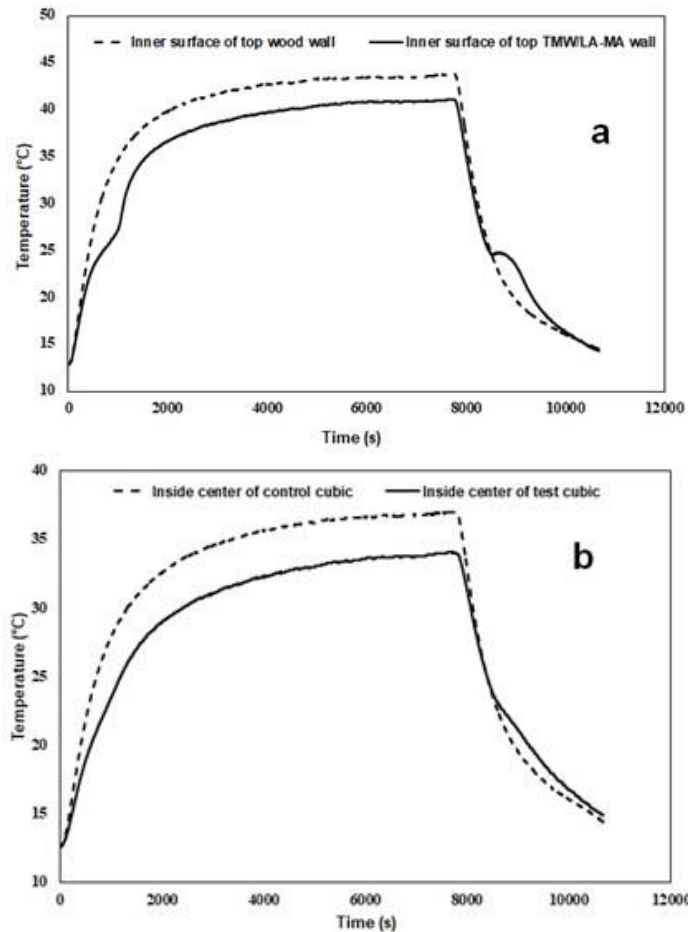
**Table 2.** TG Data of the TMW, TMW/LA-MA, and Wood

	TG (°C)				Residue (%)
	10%	30%	50%	75%	
TMW	290.17	358.15	386.06	435.16	17.39
TMW/LA-MA	153.22	183.43	299.92	376.47	10.50
Wood	313.61	359.87	386.71	439.50	18.53

It was witnessed that thermally treated wood impregnated with LA-MA (TMW/LA-MA) exhibited a lower residual weight after heating to 600 °C compared to TMW and wood. Samples showed some weight losses above 200 °C. This is because of thermal degradation of wood cell components. The thermal degradation of hemicellulose and cellulose ranged in the interval of 210 °C to 350 °C. The amorphous part decomposes to volatiles such as methanol, acetic acid, and furfural. The thermal degradation of lignin components took place only in the range of 350 to 500 °C (Hill 2006). The TG curve of LA-MA demonstrated one stage degradation between 140 and 203 °C (Hekimoglu *et al.* 2021).

### Lab-Scale Thermo-Regulative Performance

Figure 5 illustrates the heat storage properties of both the reference cubes and the PCM impregnated cubes throughout the heating and cooling phases. For improved clarity, temperature fluctuations on the inner surfaces of the top walls and at the centers of both types of cubes are depicted in comparative graphs. The temperature variations on the inner surfaces and centers of the control and test tubes are illustrated in Figs. 5a and 5b, respectively. For a while, the variations in the cells inner surface temperatures and their centers were remarkably identical, but eventually, temperature responses revealed variances. More specifically, the temperatures at specific points in the reference cell showed faster increases compared to the temperatures at corresponding points in the test cell.



**Fig. 5.** a) Temperature variations at inner surface location of top wall with/without PCM, and b) the test and control cubes at inner center locations

During the heating process in wood samples, the center temperature of the reference cell took 4780 s to reach 30 °C, whereas that temperature was achieved in a shorter time of 2622 s for the TMW/LA-MA samples. This finding indicates that the incorporation of PCM in buildings can delay the transition from comfortable temperatures to uncomfortable high temperatures, thus assisting in room temperature thermoregulation.

In a similar trend, the example in Fig. 5 was also witnessed at the inner surface temperatures of the top walls of both cubes. Wood samples reached 30 °C in 1272 s, while this time was recorded as 2214 s for TMW/LA-MA samples.

Another method to compare the thermal regulation performances of the two cells is to calculate the mean temperature values at the specified points after an equal heating duration. After being heated for 4800 s, the mean center temperatures of the reference cell and TMW/LA-MA samples were recorded as 33.6 and 30.0 °C, respectively. This indicates a mean temperature difference of 3.6 °C between the center temperatures of these two cells.

The provided comparative examples demonstrate that, during the heating period, the temperatures at the indicated points of the test cell were lower than those of the reference cell. This is attributed to the PCM's ability to absorb a certain amount of heat from the surroundings. As a result, the transfer of heat from the surroundings to the interior of the room decreases, leading to a slower rate of temperature rise.

Based on the findings from the cooling period, it was observed that the temperature at the specified point of the TMW/LA-MA samples was higher compared to the control wood. This indicates that the PCM helped to delay the overcooling of the wood. In other words, the presence of PCM resulted in a delay in the time it took for the ambient temperature to reach a lower, overcooled level. These findings indicate that the thermal energy stored within the PCM was released into the surrounding environment as the temperature decreased. As a result, the thermal performance tests showed that the integration of PCM into wood can successfully store surplus heat during hot weather, preventing a rapid increase in ambient temperature.

### WA and ASE Results

The WA and ASE results are presented in Figs. 6 and 7, respectively. The WA of control wood ranged from 63.6% after 3 h of water exposure to 150.14% after 336 h. The TMW/LAMA samples showed 3.49% of WA after 3 h to 48.92% after 336 h while TMW samples ranged from 33.56% after 3 h to 171.38% after 336 h. Based on the results, the PCM (LA-MA) impregnation decreased water uptake compared to the control samples. TMW samples impregnated with PCM drastically reduced the water uptake of ThermoWood.

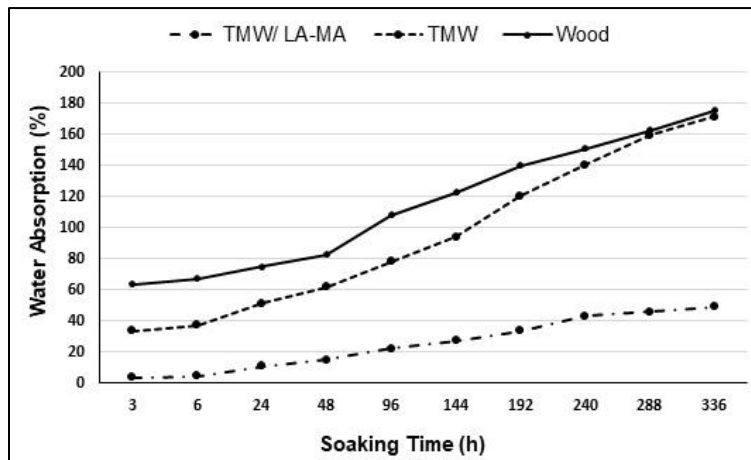


Fig. 6. Water absorption results of TMW/LA-MA, TMW, and wood samples

Accordingly, the PCM impregnation decreased water uptake compared to the control samples. The impregnation of PCMs in wood, specifically those containing fatty acids like LA and MA, effectively restricted water uptake, imparting hydrophobic properties and maintaining the wood moisture content below levels susceptible to fungal attack. To enhance the hydrophobicity of PCMs, the wood surface can be varnished or treated with water repellents, or polymers. The utilization of PCMs containing fatty acids serves the dual purpose of latent heat storage and reducing the wood moisture content below the threshold that is vulnerable to fungal infestation, making them suitable for application in multi-story wooden buildings.

The PCM-impregnated thermowood samples achieved an anti-swelling efficiency of 90.8% after 3 h, which decreased to 56.3% after 336 h, while only thermowood samples had an ASE value of 54.5% after 3 h, which decreased to 51.1% after 336 h.

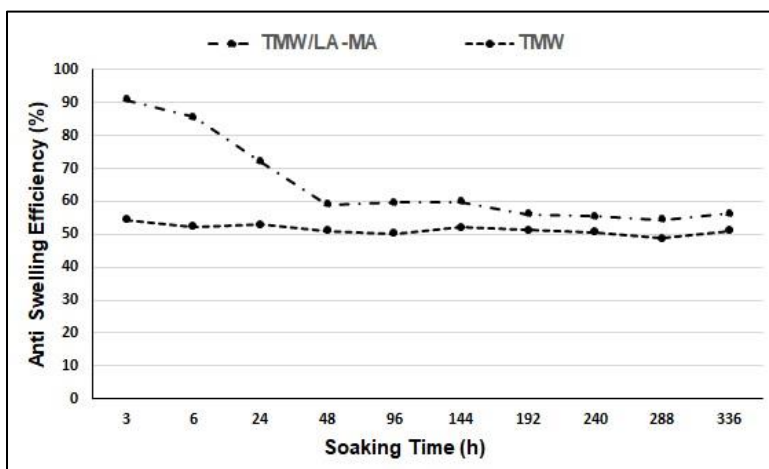


Fig. 7. Anti-swelling efficiency results of TMW/LA-MA, and TMW samples

### Mechanical Test Results

The MOR of TMW samples, TMW/LA-MA, and wood samples was 56, 119, and 121 N/mm<sup>2</sup>, respectively. The MOE of TMW, TMW/LA-MA and control samples were 445.820, 294.723, and 274.411 N/mm<sup>2</sup>, respectively.

Thermal modification decreased mechanical properties of wood 54%. This is an expected result based on literature information because thermal modification let wood cells collapse, weakening the wood and ultimately mechanical structure of wood. In contrast, LA-MA contribution to the thermally modified wood structure increased mechanical properties to the level of regular wood. The mechanical properties of LA-MA contributed wood were only 1.65% less than that of wood samples. Based on the results it can be said that LA-MA contribution to the thermally modified wood improved and recovered mechanical properties of material.

### CONCLUSIONS

In this study, the usability of thermally treated Scots pine wood impregnated with a lauric acid – myristic acid (LA-MA) eutectic mixture was investigated as a temperature regulating material in energy efficient buildings. The LA-MA mixture was considered as a phase-change material (PCM) in this study. The separate melting points of the two acids are 42.6 °C and 52.2 °C, respectively. Typically, PCMs have relatively high melting points that limit their utilization in low-temperature solar applications. However, the melting temperature of PCMs can be adjusted by incorporating a eutectic mixture of LA and MA.

1. The Fourier transform infrared (FTIR) analysis revealed a strong compatibility between thermally modified wood (TMW) and LA-MA, with the interaction between them being primarily attributed to weak physical interactions.
2. The thermal analysis indicated that the mixture of LA-MA had a melting temperature of 36.3 °C and thermally treated Scots pine with LA-MA showed the presence of a substance with a melting temperature of 33.1 °C. The results of TMW/LA-MA wood samples from DSC indicated good energy storage or release capacity.

3. The TG/DTA analyses demonstrated that PCM impregnated TMW samples left less residue (10.50%) at 800 °C than that of the untreated thermal wood at 17.4%.
4. The laboratory-scale performance test indicated that the PCM impregnated in the wood effectively retained excess heat within the environment and minimized its release to the surroundings. Furthermore, as the temperature decreased, the PCM gradually released the stored heat energy into the environment.
5. The PCM visibly decreased water uptake and raised the wood dimensional stability.
6. The result of modulus of rupture (MOR), and modulus of elasticity (MOE), measurements revealed that the LA-MA contribution to the samples recovered mechanical properties of previously thermally modified wood material.

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