Thermal and Mechanical Analysis of Plywood Boards Thermally Enhanced with Phase Change Materials

V Fernández1, C Valderrama-Ulloa1,5, F Rouault1,5, C Schmitt2,3,5, R del Río4,5, D Vasco6

1Escuela de Construcción Civil, Pontificia Universidad Católica de Chile, Chile
2Centro de Innovación en Madera UC, Pontificia Universidad Católica de Chile, Santiago, Chile
3Arquitectura, Diseño y Estudios Urbanos, Pontificia Universidad Católica de Chile, Chile
4Facultad de Química UC, Pontificia Universidad Católica de Chile, Chile
5UC Research Energy Center, Pontificia Universidad Católica de Chile, Santiago, Chile
6Departamento de Ingeniería Mecánica, Universidad de Santiago, Chile.

E-mail: c.valderrama@uc.cl

Abstract. Adding Phase Change Materials (PCM) in construction elements and materials increase their thermal mass, which may reduce temperature variation of indoor environment and improve thermal comfort of occupants. The present paper aims to study the thermal and mechanical impacts of embedding microencapsulated PCM in the adhesive of plywood boards. Mechanical properties of samples are measured using a standardized bending test; thermal mass is estimated with a homemade experimental setup based on a heated bed and two thermocouples. Tests were carried out on three different samples: a reference sample without PCM, a second sample with adhesive containing 25% of PCM, and a third sample with 30% of PCM. The most relevant results from the study showed that the mechanical properties of plywood boards were not significantly affected by the PCM, and the thermal mass was improved up to 19% on a variation of 30°C.

1. Introduction
Thermal comfort of occupants generates energy use for space heating and air conditioning. The construction industry has a negative impact on the environment. For example, the post-occupancy stage of buildings is responsible for 26% of the final energy consumption in Chile [1]. This result has led to constant research and development of new technologies and building processes to reduce energy consumption during construction and post-occupancy stages of a building. One of the problems identified in lightweight construction, such as timber-frame and metal-frame systems, is the lack of thermal mass. It can cause over-consumption of energy for heating or cooling because construction elements are unable to store excess heat and release it when needed. Whereas heavyweight structures such as concrete or masonry can regulate temperature variations of indoor environment and maintain the comfort range.

Phase Change Materials (PCMs) are a potential alternative solution to add thermal mass to lightweight construction without increasing its weight. PCM can store and release a large amount of thermal energy in a small range of temperatures because its latent heat of phase change from solid to liquid absorbs heat and inversely releases from liquid to solid. Serrano [2] showed incorporating PCM in construction elements can improve the energy efficiency of buildings.
Accordingly, embedding PCM in interior lining materials should bring thermal mass closer to the indoor environment, which may improve thermal comfort in lightweight buildings. Cerón et al. [3] experimentally study the performance of a tile with PCM as floor covering to store solar radiation; meanwhile, other studies propose to embed PCM in gypsum wallboards [4-6].

Another material used as lining materials is timber. Various studies implemented PCM in timber to improve its thermal properties. However, leakage of liquid PCM and inflammability are recurrent problems in these studies. Jamekhorsid et al. [7] tried to reduce leakage of PCM using a wood-plastic composite material made by compression; however, mechanical properties are degraded compared to wood. Liang et al. [8] imbued sawdust with fatty acids. The composite material reduces the percentage of PCM leakage and improves the thermal properties of sawdust; however, the final material was difficult to shape and get a good finishing surface for lining material. Jeong et al. [9] studied a composite material based on timber, PCM, and resin for a floor covering; however, the authors did not succeed in the desired shape for a final product. This short literature review shows that there is interest in improving the thermal mass of wooden lining material, but there is room for improvement in all the researched solutions.

Therefore, the present research project aims to develop an improved thermal mass solution of timber as a lining material with an embedded PCM without negatively impacting mechanical properties and inflammability. Accordingly, this paper analyzed the mechanical and thermal impacts of embedding microencapsulated PCM in the plywood adhesive. Since plywood is made of a thin layer of wood veneer, it makes it possible to bring the PCM close to the indoor environment. It is expected that PCM can improve the thermal mass of the plywood boards without significantly affecting the mechanical properties of the base material, which could be used as a finishing and thermal mass component in buildings.

2. Methodology
The methodology used to analyze the thermal and mechanical impacts of embedding PCM in plywood boards consists of three stages. Firstly, two samples with different amounts of PCM and a reference sample of plywood board 300x300 mm were made by gluing and pressing processes. Then the boards were divided into eight rectangular samples for the bending test. Secondly, a bending test was carried based on the standard UNE EN 310 [10]. Finally, a simple thermal test was carried out on 50x50 mm samples using a heated bed and two thermocouples. Details of the different stages are described in the following sections.

2.1 Samples preparation
Three plywood boards 300 x 300 mm approx. were made. Each board was made of three softwood veneers selecting the best ones. The weight of the three wooden layers was measured before gluing to know the exact amount of adhesive and PCM in each sample.

The PCM used in this study is a microencapsulated paraffin wax whose commercial name is MikroCapsPCM28. Table 1 shows the physical characteristics of the microencapsulated PCM, which has an effective latent heat of 189 J/g and a phase change temperature of 28°C approx.

| Composition | Technical data |
|-------------|----------------|
| Classification | Phase change materials microcapsule |
| Type of membrane | Melamine-formaldehyde |
| Type of PCM | Paraffin wax |

Table 1. Physical characteristics of the microencapsulated PCM - Source: by authors
Glue is made of a mix of phenol/formaldehyde with a 100:20 ratio. One of the boards is made of this mix with PCM as a reference. For the other two boards, microencapsulated PCM is added to the mixture in a proportion of 25% and 30% by mass. Table 2 summarizes the amount of each component of the glue mixture.

Table 2. Glue composition for the different samples

|     | PCM (%) | PCM (g) | Phenol (g) | Formaldehyde(g) |
|-----|---------|---------|------------|-----------------|
| A   | 30      | 15      | 50         | 10              |
| B   | 25      | 12.5    | 50         | 10              |
| C   | 0       | 0       | 50         | 10              |

As noted in Table 2, Sample C is the reference board without PCM; sample B has a 25% by glue mass of PCM, and sample A has 30% by glue mass of PCM.

The gluing process starts by mixing phenol/formaldehyde glue and the PCM until obtaining a homogeneous mixture. Then, the mixture is applied to one face of each wood veneer covering the whole area. Wood veneers are superposed, with the grain rotated up to 90 degrees from one another. In the case of sample C (without PCM), the glue application was smooth and homogeneous, whereas the glue in sample B (25% of PCM) was thick and harder to apply. Sample A (30% of PCM) was too thick for a uniform application, which made an impossible higher proportion of PCM in the glue mixture. Finally, the three samples were piled separated by a nylon film between samples to avoid sticking one to another (fig. 1). Samples were pressed for 24 hours to ensure that the adhesive was completely dry.
After pressing the samples, the weight of each sample is measured to compare with the initial mass measurement and estimate the amount of glue and PCM. Table 3 summarizes the results for each sample.

Table 3. Weight measurement of wood samples before and after gluing process

| Sample | Initial mass (g) | Final mass (g) | Mass variation (g) | Mass of PCM (g) |
|--------|-----------------|----------------|--------------------|-----------------|
| A      | 335.7           | 395.4          | 59.7               | 17.9            |
| B      | 343.3           | 387.9          | 44.6               | 11.2            |
| C      | 344.5           | 375.3          | 30.8               | 0               |

As observed in Table 3, the most significant weight variation is noted in sample A and the lowest in sample C, which contains the reference glue. The thickness of the mixture helped to keep a larger amount of glue between wood veneers and, consequently, a larger amount of PCM. Finally, the 300x300 mm samples are cut in smaller samples of 200x50 mm for the bending test and 50x50 mm samples for the thermal test.

2.2 Bending Test
The bending test aims to check if there is a variation of the bending strength and elasticity modulus of plywood embedded PCM in comparison with the reference sample without PCM. Modulus of elasticity and bending strength are calculated using the standard UNE EN 310 as a reference.

According to this standard, the samples of the bending test must be rectangular with a width of 50 ± 1 mm, and the length should be 20 times the sample thickness plus 50 mm. Then, sample boards A, B, and C are cut into eight pieces of 50 x 200 mm each. Four samples were made with the external layer grain parallel to the long side of the sample and four samples with the external layer grain in the perpendicular orientation.

The span between support bars is adjusted to be 20 times the thickness of samples. Since the thickness of all the samples is 7 mm, the span is then 140 mm. The bending load is applied in the center between the support bars, as shown in Figure 2, with a constant moving speed.

![Figure 2](source: by authors, from [10])

A displacement at a constant speed is applied at 15 mm/min to samples with the perpendicular grain, and at 10 mm/min to samples with parallel ones. The test lasts less than a minute and a half as specified in the standard. For half of the samples, the load was applied on one face. For the other half, the load was applied on the other face complying with the standard.

Displacement and force are registered each second by the bending test machine. Exported data from each test allow to calculate the modulus of elasticity ($E_m \ [N/mm^2]$) and the bending strength ($f_m \ [N/mm^2]$) according to equations 1 and 2:
\[ E_m = \frac{l_1^3(F_2 - F_1)}{4bt^3(a_2 - a_1)} \]  
Equation 1

\[ f_m = \frac{3F_{max}l_1}{2bt^2} \]  
Equation 2

Where:
- \( l_1 \): Span between support bars [mm]
- \( b \): Piece width [mm]
- \( t \): Piece thickness [mm]
- \( (F_2 - F_1) \): Load increase in linear behavior zone of load vs. displacement. \( F_1 \) corresponds to 10% and \( F_2 \) to 40% maximum load [N]
- \( (a_2 - a_1) \): Displacement in the central zone of the sample at \( F_1 \) and \( F_2 \) loads [mm]
- \( F_{max} \): Maximum load [N]

2.3 Thermal Tests

The incorporation of PCM in plywood boards is expected to impact positively on the thermal mass of the lining material. The thermal mass of a component or material refers to its capacity to store thermal energy and gradually release it. Thermal mass can reduce the energy use of heating and cooling systems because it maintains the indoor temperature in the comfort zone.

A homemade experimental setup has been developed to estimate the impact of PCM on the thermal behavior of plywood samples. The setup shown in Figure 3 is composed of a heated bed and two thermocouples located on both sides of the sample. As shown in Figure 3, the experimental setup is insulated with expanded polystyrene to ensure unidimensional heat flux from the heated bed to the opposite side of the sample. The heated bed and the thermocouples are connected to an Arduino controlling the temperature of the heated bed. It also registers temperatures on both sides of the sample.

![Figure 3](image)

Figure 3. Sketch of the experimental setup(a). Experimental setup without the sample and the heated bed (b). Complete experimental setup(c)

From the samples for the bending test, 50 x 50 mm samples of each type (A, B and C) were cut for the thermal test, selecting those in better condition. This test measures the samples’ thermal response with PCM and compares it with the reference sample.

Since the sample is completely insulated, it can be considered as a unidimensional problem in which the Fourier can be written as follows [7]:

\[ \rho cV \frac{dT_2}{dt} = \frac{\lambda S}{e}(T_1 - T_2) \]  
Equation 3

Assuming that the heated bed’s temperature is constant during the test. The solution of the previous first order differential equation can be expressed as:
\[
\frac{T_2 - T_1}{T_i - T_1} = e^{-\frac{t}{\tau}}
\]
Equation 4

Where:
\[
\tau = \frac{\rho c V e}{\lambda S}
\]
Equation 5

Thus:
\[
\tau = \frac{\rho c e^2}{\lambda}
\]
Equation 6

Where:
- \( T_1 \) Temperature in heated bed, [°C].
- \( T_i \) Initial temperature in point 2 [°C].
- \( T_2 \) Temperature in point 2 of the sample [°C].
- \( t \) Time, [s]
- \( \lambda \) Thermal conductivity of the sample [W/m K]
- \( c \) Specific heat of the sample [J/kg K]
- \( e \) Sample thickness [m]
- \( \rho \) Sample density [kg/m³]
- \( \tau \) time constant of the sample

3. Results and discussion

3.1 Bending Test Results

During the bending test, 20 samples in total were tested, gathered by the amount of PCM and grain direction according to the sample length. The water content of the sample was between 6% and 8% during the bending test. The modulus of elasticity (\( E_m \)) and bending strength (\( f_m \)) were calculated from the data obtained during each test. Figure 4 shows the results for the modulus of elasticity by the amount of PCM and the grain direction. The histogram bars represent the mean value of measurements, and the points represent the minimum and maximum values obtained for each type of sample.

Thus, it can be observed that in perpendicular grain samples (dark grey bars), the variation of the modulus of elasticity between the different content of PCM is minimum, having a value of 465 [N/mm²] in the reference board. Regarding the mechanical performance of the sample with parallel grain (light grey bars), the reference board has a modulus of elasticity of 6,442 [N/mm²]. The mean \( E_m \) for the sample with PCM is slightly lower than the mean for the reference sample. A similar trend can be observed between the maximum and minimum values of the samples. The samples with 25% of PCM present a higher variation of 1,787.06 N/mm² less than the reference samples.
On the other hand, Figure 5 shows the consolidated results of bending strength. The dark grey bars present the results obtained with perpendicular grain in which the mean bending strength of the reference sample is 13 [N/mm²]. It can be noted that samples with PCM have slightly the same bending strength as the reference sample. The results for parallel grain are shown in light grey. It can be observed that samples with PCM have better bending strength than the reference sample.

According to the results of bending strength and modulus of elasticity, it is possible to conclude that incorporating PCM up to 30% to the adhesive mass does not significantly affect the mechanical properties of plywood boards.

### 3.2 Thermal Behavior Test Results

The thermal test consists of stabilizing the experimental device at 20°C approx. for 20 minutes, and then the heated bed generates a step input of 50°C. The experiment lasts until the opposite side of the sample reaches the input temperature, which is 50 min approx.
The thermal test was carried out for each of the three types of samples. The thermal response of the samples can is represented in Figure 6 independently of the input temperature using the expression of Equation 4. This representation makes it possible to compare tests with different input temperatures since control by the Arduino system is not accurate enough to repeat the same input temperature in every test.

![Temperature Response of Plywood Boards](image)

**Figure 6.** Temperature Response of Plywood Boards

Since density and thermal conductivity were not featured, it is not possible to accurately calculate the equivalent specific heat of the samples. However, density and thermal conductivity can be considered unchanged between the three samples. Therefore, it is possible to evaluate the variation of thermal mass (see Equation 7) considering that thickness is also the same between the samples:

\[
\frac{\tau_{PCM}}{\tau_{Base}} = \frac{c_{PCM}}{c_{Base}}
\]

**Equation 7**

The value of the time constant \(\tau\) for each sample is calculated using the method of least squares between the experimental results and the theoretical response curve. Table 4 shows the estimated time constants of each sample.

| Sample       | \(\tau\) |
|--------------|---------|
| A            | PCM 30% | 252    |
| B            | PCM 25% | 249    |
| C            | Base    | 211    |

**Table 4.** Estimated Time Constants (\(\tau\)) for Each Sample
Comparing the time constant of samples with PCM against the reference sample, the sample with 25% of PCM improves the specific heat by 18% meanwhile the sample with 30% of PCM improves the specific heat by 19%, considering a temperature variation of 30°C from the initial to the final temperature of the sample. Although the thermal mass added by the PCM is not fully featured, these preliminary results show that embedding microencapsulated PCM in plywood boards has a positive impact on their thermal mass. Finally, no leakage of PCM was observed during the various tests, which lead to conclude that microcapsules were not damaged during the fabrication process of the samples.

4. Conclusions
The present study showed that the thermal mass of plywood boards could be improved by embedding microencapsulated PCM in the adhesive layers. To this end, a bending test was carried out for samples with 25% and 30% adhesive mass; the results were compared with the properties of a reference sample without PCM. Experimental results confirm that there is no significant negative impact on the mechanical properties of embedding the adhesive mass up to 30% of PCM. Finally, the results of a basic thermal test showed that PCM improved the thermal mass of the plywood board by up to 19% on a variation of 30°C.

Although these results are highly encouraging, further tests are necessary to evaluate the maximum amount of PCM that can be embedded in a plywood board. Moreover, thermal properties should be accurately defined to simulate the impact on energy demand using a building performance simulation software like EnergyPlus. Lastly, a full-scale plywood board will be made to measure its thermal behavior in real conditions.

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