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MODELING AND ANALYSIS OF TEMPERATURE DISTRIBUTION ACROSS THE CROSS-SECTION OF FLAT-PRESSED WOOD-POLYMER COMPOSITES DURING COOLING STAGE

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ABSTRACT

This study is aimed at formulating a mathematical model describing the thermal dissipation kinetics during the post-processing cooling of flat-pressed wood-polymer composites (FPWPC). The dependence of the composite cooling time and the spatiotemporal temperature distribution across its thickness on the wood particle content, initial surface temperature, and bulk density are elucidated in the study. Analysis of the core layer thermal profile revealed three distinct phases: an initial temperature rise, a thermal maximum, and a conduction cooling phase. The findings indicate that both the wood particle content and the initial surface temperature of the FPWPC significantly influence the rate of thermal dissipation. Elevated initial surface temperatures (200°C) resulted in an initially accelerated cooling rate followed by a deceleration. Composites with a higher wood particle content (60%) exhibited slower cooling rates, attributed to the lower thermal conductivity of wood compared to the thermoplastic polymer matrix, leading to enhanced thermal retention. The bulk density of the FPWPC plays a critical role in its thermal management, affecting its specific heat capacity, thermal conductivity, and convective heat transfer efficiency. The derived mathematical model has the potential to optimise FPWPC manufacturing processes.

Keywords: flat-pressed wood-polymer composites; post-processing cooling process; cooling time; cooling temperature.

INTRODUCTION

Wood–polymer composites (WPCs) are considered promising materials due to their advantageous operational characteristics and broad applicability across various industrial sectors (Klyosov, 2006). WPCs can be manufactured using multiple processes, including extrusion, injection moulding, and compression moulding, depending on the intended geometry and application of the final product (Klyosov, 2006). Among these, extrusion is the most commonly employed method for WPC production in the United States and Europe (Rowell, 2005), primarily used to create continuous profiles with limited cross-sectional complexity. In addition to extrusion, WPCs can also be produced via flat pressing in hot presses (Ayrilmis and Jarusombuti, 2011; Benthien and Thoemen, 2012; Lyutyy *et al.*, 2014). This hot-pressing method has been the focus of significant academic research aimed at improving the structural and functional performance of flat-pressed WPCs (FPWPCs) (Ayrilmis and Jarusombuti, 2011; Benthien and Thoemen, 2012; Lyutyy *et al.*, 2014). Mathematical models have been developed to optimize the hot-pressing process, thereby enhancing efficiency and product consistency (Lyutyy *et al.*, 2024). A critical yet often underexplored aspect of FPWPC production is the post-pressing cooling stage, which plays a crucial role in consolidating the composite final properties. Although some studies refer to this stage simply as the final cooling phase – typically concluding when the material reaches approximately 50 °C – they often lack a detailed examination of key process parameters, such as cooling time and the temperature of the cooling surfaces (Benthien and Thoemen, 2012; Benthien and Thoemen, 2013).

Previous research has investigated optimal cooling strategies for thermoplastic composites in the post-manufacturing phase (Sonmez and Eyol, 2000). One such study focused on determining the most effective cooling regime to reduce processing time during the cooling stage of APC-2 laminate press moulding. Additionally, an experimental investigation examined the thermal dissipation behavior of WPCs that were initially heated to 150°C in an electric furnace and subsequently cooled at ambient conditions (21°C) (Matthews *et al.*, 2015).

Despite the recognized importance of the thermal dissipation stage in the production of flat-pressed wood–polymer composites (FPWPCs), a review of the existing literature reveals a significant gap in research addressing the mathematical modeling of the cooling process in these materials. Therefore, the objective of the present study was to develop a mathematical model capable of predicting the cooling duration of FPWPCs produced in periodical action presses. The goal was to determine the optimal cooling time required for the core layer of the composite to reach the polymer solidification temperature.

MATERIALS AND METHODS

Development of the mathematical model

The time required to close and open the press plates, as well as the time to increase and decrease the pressure, are determined by the type of flat pressing equipment and any modifications made to it. Primarily, the cooling time for FPWPC panels is determined by the time to reach a predetermined temperature in the core layer (*H*) (Fig. 1).

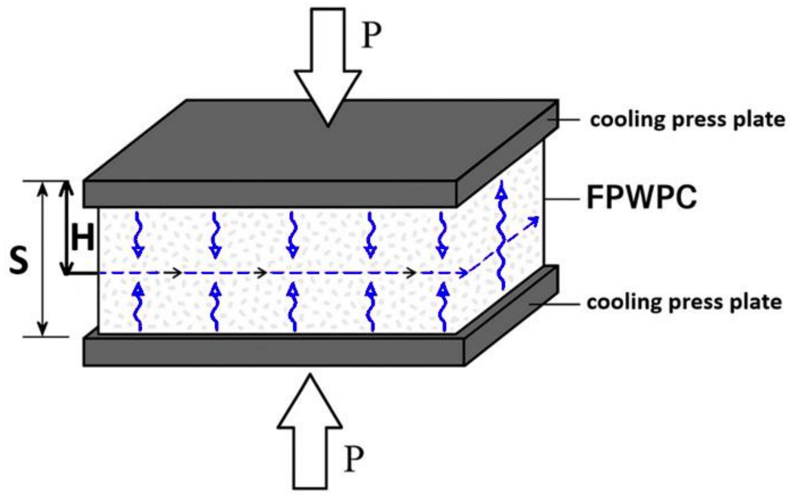

Fig. 1 Cooling model of FPWPC after hot-pressing.

In the case of one-dimensional transient heat conduction, incorporating Fourier's Law and principles consistent with the Second Law of Thermodynamics, the heat conduction equation takes the following form:

$$\frac{dT}{dt} = -\alpha \cdot \frac{d^2T}{dx^2}, \tag{1}$$

Where: $T\ (x,t)$ – temperature at point x at time t; α – the thermal diffusivity (α), a property determined by:

$$\alpha = \frac{\lambda_{eff}}{\rho \cdot C_{fpwpc}}, \tag{2}$$

Where: λ_{eff} – effective thermal conductivity of FPWPC; ρ – density of FPWPC; C_{fpwpc} – heat capacity of the FPWPC.

FPWPC consists from wood particles and thermoplastic polymer, therefore effective thermal conductivity of FPWPC can be calculated using formula:

$$\lambda_{eff} = \lambda_{wood} \cdot \varphi_{wood} + \lambda_{pol} \cdot (1 - \varphi_{wood}), \tag{3}$$

Where: λ_{wood} and λ_{pol} – are the thermal conductivities of wood and polymer, respectively; φ_{wood} is the volumetric fraction of wood particles in the composite material, expressed as a fraction.

Therefore, the volumetric fraction of wood particles can be calculated in the following manner:

$$\varphi_{wood} = \frac{V_{wood}}{V_{WPC}} \text{ or } \varphi_{wood} = \left(1 - \frac{V_{pol}}{V_{WPC}}\right), \tag{4}$$

Where: V_{WPC} is volume of FPWPC and V_{wood} is the volume of wood particles within the FPWPC.

The thermal conductivities of wood and thermoplastic polymer (in our mathematic we will choose high-density polyethylene (HDPE)) are determined using experimental linear equations (Prisco, 2014):

$$\lambda_{pol}(T) = 0.429 - 0.99 \cdot 10^{-3} \cdot T\ ; \tag{5}$$

$$\lambda_{wood}(T) = 0.361 + 1.876 \cdot 10^{-4} \cdot T \tag{6}$$

The specific heat capacity of the FPWPC can be calculated using the following equation:

$$C_{fpwpc} = C^{W}_{wood} \cdot \varphi_{wood} + C_{pol} \cdot (1 - \varphi_{wood}), \tag{7}$$

Where: $c^{W}{}_{wood}$ and c_{pol} are the specific heat capacities of moist wood particles and thermoplastic polymer, respectively.

Then the specific heat capacity of moist wood particles, considering their moisture content, can be determined as follows (Thoemen and Humphrey, 2005):

$$C_{wood}^{W}(T,W)=\frac{1131+4.19\cdot T+4190\cdot W}{(1+W)\cdot 1000} \quad (8)$$

The specific heat capacity of a HDPE is temperature dependent and can be calculated by (Gaur and Wunderlich, 1981):

$$C_{pol}(T)=\frac{2550+3.43\cdot(T-130)}{1000} \quad (9)$$

An explicit scheme of the finite difference method is used for the numerical solution. The discretization in time and space is presented as follows.

Spatial distribution:

$$x_i=i\cdot\Delta x; \quad (10)$$

$$i=0,1,2,3,....,Nx-1 \quad (11)$$

Temporal distribution:

$$t_{ni}=n\cdot\Delta t; \quad (12)$$

$$n=0,1,2,3,....,Nt \quad (13)$$

Spatial step:

$$\Delta x=\frac{S}{Nx-1}\ , \quad (14)$$

Where: S – thickness of FPWPC (S = 2 H).

Temporal step:

$$\Delta e=0.1\cdot\frac{\Delta x^2}{\alpha} \quad (15)$$

The discretization of the Fourier equation results in:

$$T_i^{n+1}=T_i^n+\frac{\alpha\cdot\Delta t}{\Delta x^2}\cdot\left(T_{i+1}^n+2\cdot T_i^n+T_{i-1}^n\right), \quad (16)$$

Where: T_i^n– temperature at the *i*-th node at the *n*-th time step; T_{i-1}^n, T_{i+1}^n – temperature at the adjacent nodes; $\frac{\alpha\Delta t}{\Delta x^2}$ – dimensionless coefficient.

Subsequently, the initial conditions can be formulated in the following manner.

At the onset of the modeling process, the temperature distribution is defined through the thickness of the FPWPC:

$$T(x,0)=\begin{cases}T_{surface,,(x=0)or(x=S)}\\ T_{depth,,(x=H)}\end{cases} \quad (17)$$

And boundary conditions will be:

$$T(o,t)=T(S,t)=T_{press} \quad (18)$$

Within the numerical discretization:

$$T_0^n=T_{Nx-1}^n=T_{press} \quad (19)$$

The finite element method (FEM) was employed as the numerical approach for solving the boundary value problem. FEM is based on the principle of approximating a continuous function with a discrete model composed of piecewise constant functions defined over a finite number of subdomains known as finite elements. The geometric domain of interest is discretized into these elements, within which the unknown function is approximated using trial functions. These trial functions are required to satisfy both inter-element continuity and the boundary conditions specified by the problem.

To implement the developed model, the Matlab R2021b (9.11) computational environment (MathWorks, Natick, MA 01760-2098, USA) was utilized, specifically the Matlab Partial Differential Equation Toolbox (PDE Toolbox), which supports FEM-based simulations. The toolbox graphical user interface (GUI), accessed via the functions “pdeinit” and “pdetool”, facilitates the interactive setup of the PDE model. This includes defining the geometry of the domain, specifying boundary conditions, selecting the equation type and its coefficients, generating a computational mesh, solving the problem, and visualizing the results.

Given that surface temperature after pressing, wood mass fraction, and board density are variable factors in the cooling process, a custom Matlab function, “calculate.m”, was developed. This function accepts these parameters as input and returns numerical simulation results, specifically, temperature distributions at the mesh nodes over time, presented in matrix form.

Graphical representations of the simulated data were generated for an FPWPC sample with a thickness of 18 mm, assuming a constant cooling platen temperature of 25 °C. The initial temperature of the core layer was set at 120 °C. The simulation was concluded when the temperature at the composite core decreased to 50 °C. The moisture content of wood particles was 3%.

The parameters used in the simulation of the FPWPC cooling model are summarised in Table 1.

Tab. 1 Variable parameters.

Conditions	Values
Initial surface temperature (°C)	160, 180, 200
Wood particles content, (%)	20, 40, 60
Density of FPWPC (kg/m^3)	800, 900, 1000

RESULTS AND DISCUSSION

The execution of the mathematical model yielded a plotted relationship illustrating the dependence of the FPWPC cooling time on its initial surface temperature, as well as the spatiotemporal temperature distribution across the material cross-section throughout the entire cooling cycle (Fig. 2).

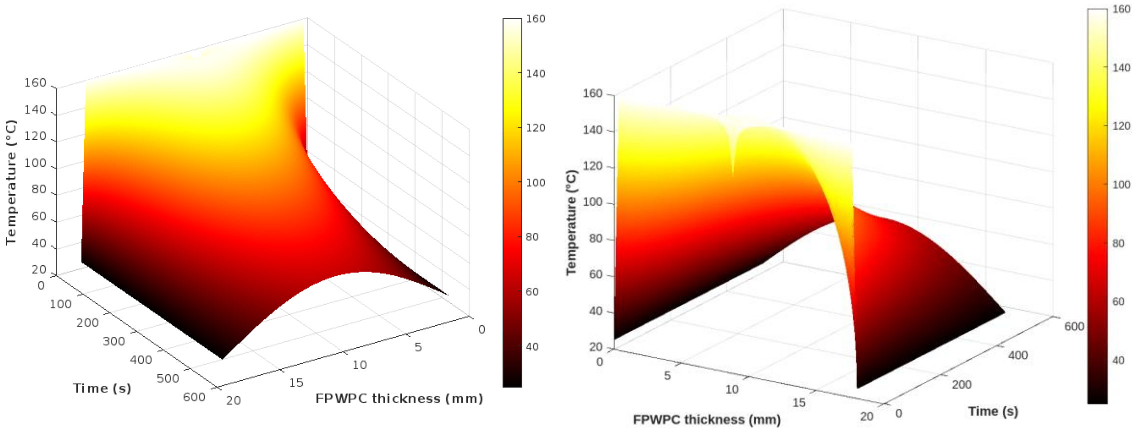

Fig. 2 Temperature distribution within the FPWPC across its thickness until the internal temperature reaches 50 °C, with an initial surface temperature of 160 °C and a composite density of 1000 kg/m³.

The non-uniform cooling behavior of FPWPC along its thickness is evident and results from the varying heat transfer rates in different layers of the composite. At the onset of the cooling phase, the surface regions exhibit the highest temperature, corresponding to the press plate temperature during the hot-pressing stage. In contrast, the core layer initially exhibits a lower temperature – approximately 10 °C above the fusion temperature of the thermoplastic polymer (Lyutyy *et al.*, 2024). However, as cooling progresses, the surface layers are the first to experience a temperature drop, while the core temperature continues to rise due to thermal inertia. This heat redistribution from the surface to the core creates a steep temperature gradient across the thickness of the material.

Temporally, the cooling of the FPWPC core layer can be divided into three distinct phases:

1. initial temperature rise **(0~40 s)**;
2. thermal maximum **(~40~60 s)**;
3. convective cooling phase **(~60~800 s)**.

In the first phase – **the initial temperature rise (0~40 s)** a rapid increase in the core temperature is observed, particularly during the first 10–20 seconds. This occurs due to the significant temperature difference between the hotter surface layers and the cooler core. As heat from the surface begins to conduct inward, the core temperature increases sharply, driven by the established thermal gradient. The rate and duration of this temperature rise are influenced by factors such as the initial surface temperature, wood particle content, and bulk density of the FPWPC (Fig. 3). A greater temperature gradient between the surface and the core layers leads to a more extended transition period before the composite enters the cooling phase proper. It is important to note that the core temperature does not rise instantaneously; instead, it increases progressively as thermal energy accumulates in the upper layers before being conducted inward.

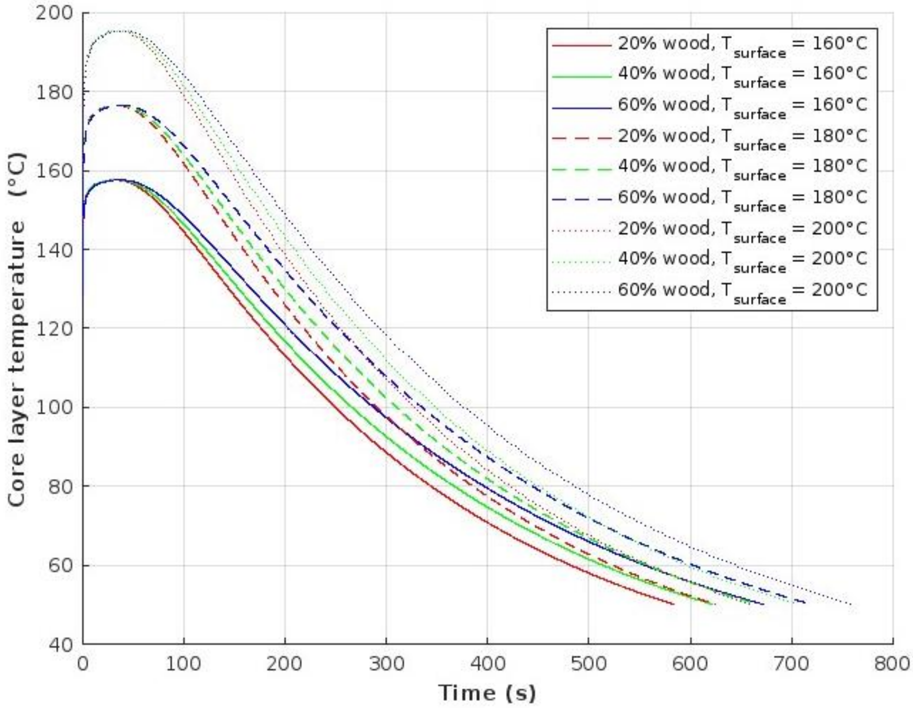

Fig. 3 Temperature distribution curves in the core layer of FPWPC over time at different initial surface temperatures and wood particle content, at a composite density of 1000 kg/m^3.

The second stage of the cooling process, referred to as the **thermal maximum phase (~40–60 s)**, is characterized by the attainment of a peak temperature within the core layer of the FPWPC. This peak occurs as a result of delayed heat transfer into the core, a phenomenon governed by the thermal inertia of the composite. Initially, heat accumulates in the surface layers due to their direct exposure to the hot press plates. As the cooling process begins, this accumulated heat gradually diffuses inward, resulting in a temperature rise within the core and ultimately forming a distinct temperature peak.

Once the temperature in the core layer reaches its maximum, heat begins to dissipate more rapidly due to two simultaneous processes:

– The part of the heat is transferred from the core to adjacent, cooler layers;

– The surface of the composite, already in contact with the press cooling plates, begins to cool, reducing the thermal influx into the interior.

As a result, the core temperature gradually begins to decline, marking the transition to the third cooling phase. Notably, the magnitude and timing of the thermal peak are strongly influenced by both the initial surface temperature and the wood particle content of the FPWPC. A higher initial surface temperature (e.g., 200 °C) results in a more pronounced and earlier peak. Similarly, increasing the wood particle content delays the thermal maximum and elevates its magnitude due to the wood lower thermal conductivity compared to the thermoplastic matrix. For instance, at 20% wood content, the temperature peak is lower, and cooling begins sooner, whereas at 60%, the peak is higher and occurs later, indicating enhanced heat retention.

This phase can be further subdivided into three sub-phases:

- **Rapid temperature peak**, especially for composites with high initial surface temperatures (e.g., 200 °C);
- **Gradual temperature stabilization**, where the rate of increase levels off;
- **Onset of temperature decline, indicating transition into the cooling phase.**

The third stage – **the cooling phase (~60–800 s)** begins once the core temperature peaks and subsequently decreases exponentially. The core does not cool instantaneously; instead, heat continues to transfer into deeper layers before being entirely dissipated. During the early stages of this phase, a significant temperature gradient exists between the composite surface and the press plates, driving rapid heat transfer. However, as this gradient diminishes, the cooling rate progressively slows. This transition typically occurs between 300 and 400 seconds.

The cooling rate in this phase remains dependent on both the initial surface temperature and wood content. FPWPCs with higher initial surface temperatures cool rapidly at first but exhibit slower rates later in the cycle. Meanwhile, composites with higher wood content (60%) exhibit slower overall cooling due to wood's lower thermal conductivity and greater thermal mass. As cooling progresses, the temperature curves of the core layer gradually converge toward an asymptotic value, stabilising around 50°C, indicating the completion of the cooling process.

The time evolution of this phase can be divided into two distinct sub-phases:

- **Fast cooling (~160~300–400 s)**: Characterized by a rapid temperature drop accounting for approximately 50–70% of the total cooling time;
- **Slow stabilization cooling (~300–400–800 s)**: The rate of cooling diminishes as thermal gradients decrease and the temperature in the core layer approaches equilibrium. Eventually, the core layer temperature stabilizes at a temperature close to the target threshold of 50 °C.

A comparison of the model-generated cooling curves with the experimental results reported by Matthews *et al.* (2015) reveals a substantial similarity. In their study, the cooling curve was divided into two distinct curves based on observations of different cooling rates near the melt temperature of 125 °C. Initially, the cooling rate decreased rapidly until it reached the hot-melt temperature of 125 °C of the composite material. We can see the same cooling dynamics in the curves shown in Fig. 2. At the beginning of the process, the surface layers of the WPC cool rapidly with a gradual transfer of heat to the inner layers, as a result of which the cooling process slows down and transitions to the slow stabilization cooling phase. However, it is essential to note that the referenced study measured surface temperatures under ambient cooling conditions, whereas the present model simulates forced cooling between press plates – conditions more representative of industrial FPWPC production.

In a study by Grzybek *et al.* (2024), the panel ability to absorb and release thermal energy of bio-based composites using sawmill by-products, recycled paper, and bio-binders was investigated. During the cooling process, it is observed that all investigated samples start to cool down until they reach the phase transition temperature (solidification temperature), at which the samples start to change phase from liquid to solid. The starting temperature of the cooling process was 40 °C, and then it was placed in a climate chamber with a temperature set at 0°C. The cooling curves are similar to the last stage of FPWPC.

Similar cooling curves were also observed by García-Martínez *et al.* (2025), but in this case, cooling took place in an autoclave under pressure. At the same time, the material used for testing was a carbon fibre H-beam. Both experimental and model processes were investigated. The results show that both pressure and temperature variation curves follow a physically consistent pattern, confirming that the model operates correctly.

Additionally, the simulation revealed that composites with higher bulk densities (e.g., 1000 kg/m^3) cool more slowly than those with lower densities (e.g., 800 kg/m^3) due to their increased thermal mass and reduced heat transfer efficiency (Fig. 4).

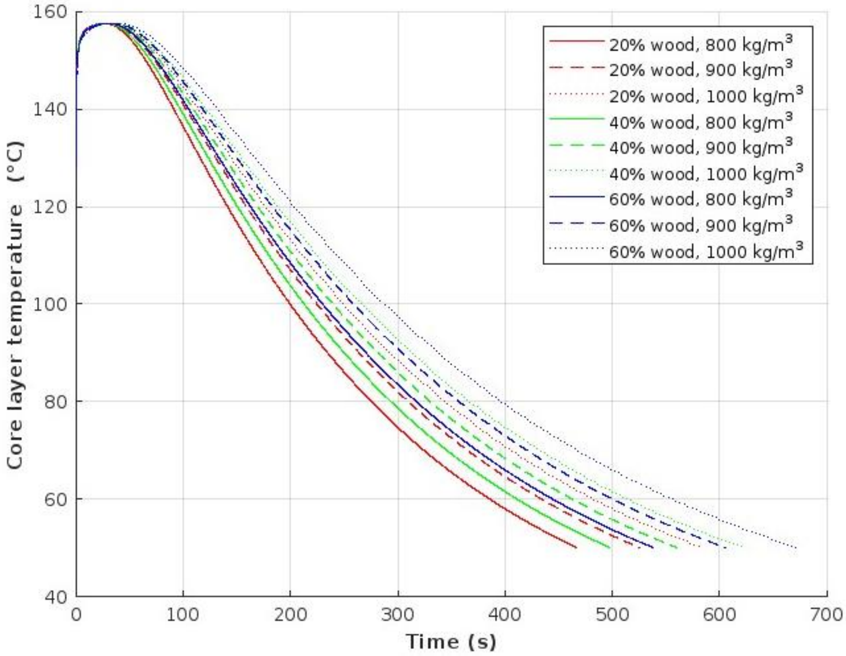

Fig. 4 Curves of temperature distribution in the core layer of FPWPC in time at different densities and contents of wood particles and at an initial temperature of the composite surface of 160 °C.

Further insights results are supported by the findings of Deliiski *et al.* (2024), who investigated the thermal energy components necessary for thawing logs. Their study presents a comprehensive model for calculating the specific heat capacity and latent heat components of wood during phase transitions from a frozen to an unfrozen state. In the context of FPWPC cooling, the temperature range remains above freezing, and the understanding of energy components from thawing logs helps clarify the complex interplay of heat transfer, storage, and phase-related thermal inertia in wood-containing composites. This observation aligns with the non-uniform cooling profiles observed in the FPWPC cross-section, where surface layers cool faster while the core retains heat longer due to delayed thermal diffusion.

This behavior can be attributed to the fact that as the density of the FPWPC increases, so does its mass and, consequently, its capacity to store thermal energy. As a result, denser composites require more time to dissipate the accumulated heat, leading to a slower cooling rate. Although materials with higher density often exhibit greater thermal conductivity, promoting faster internal heat transfer, the increased heat capacity frequently outweighs this effect. Therefore, the net effect is that denser FPWPCs tend to cool more slowly than their less-dense counterparts.

CONCLUSION

It was observed that the cooling of flat-pressed wood-polymer composites (FPWPCs) is a non-linear process characterized by an initially rapid temperature drop followed by a gradual deceleration. One of the key factors influencing the cooling rate is the wood particle content. An increase in wood content leads to a reduction in thermal conductivity, thereby slowing down heat transfer and prolonging the cooling duration of the composite inner layers. In addition to the wood content, the thickness of the FPWPC significantly impacts its cooling behavior. While the surface layers cool rapidly due to direct exposure to the cooling plates, the core retains heat for a more extended period, resulting in a pronounced delay in reaching thermal equilibrium. The initial surface temperature also plays a critical role. A higher initial surface temperature extends the pre-cooling phase, delaying the onset of actual cooling in the core. However, once cooling begins, composites with higher initial temperatures exhibit a faster initial cooling rate due to the larger temperature gradient. This effect is temporary, as a noticeable slowdown typically occurs between 300 and 400 seconds into the cooling process. The bulk density of the FPWPC further influences cooling performance by affecting its heat capacity, thermal conductivity, and overall heat dissipation efficiency. Lower-density composites cool more rapidly, while higher-density composites retain heat for longer durations. This difference becomes especially pronounced after approximately 100 seconds of cooling when thermal inertia in denser materials begins to dominate the process. The developed mathematical model can be applied to calculate the cooling time of flat-pressed wood-polymer composites (FPWPCs) fabricated with various thermoplastic polymer matrices.

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