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ORIGINAL ARTICLE

Influence of the microwave-accelerated process on the drying kinetics, mechanical properties and surface appearance of rubberwood (*Heavea brasiliensis*)

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Abstract

This paper investigated the impact of microwave-assisted drying on the energy consumption, drying rate, surface temperature, drying time, static bending properties, and quality of dried rubberwood (*Heavea brasiliensis*) using different scenarios of combined microwave and convective air drying. Combined microwave and convective drying experiments were performed at frequencies of 2.45 ± 0.05 GHz and microwave power of 4.8 kW, air drying temperatures of 30, 50, and 70 °C, and air drying velocity of 5.0 m/s using a multifeed microwave-convection hot air and continuous belt system (CMCB). The test results showed that rubberwood drying in a microwave system with multiple wave feeding and convection heating together with a conveyor in a hybrid system reduced the moisture of rubberwood from 70% to an average of approximately 20%. In addition, the most suitable conditions for the experiment were drying at an air temperature of 30 °C for 30 min and then in a microwave at 30 °C, compared to 30 °C for 30 min and then turning on the microwave at temperatures of 50 and 70 °C. The minimum energy consumption for drying with this method was 16.3 kWh. The results also indicated that the end quality of rubberwood samples dried under microwave-assisted drying was similar to that of conventional drying but better than that of rubberwood samples dried under combined microwave and air drying.

1 Introduction

Rubberwood is a widely used utility wood due to its high density, tempered colour, dimensional stability (swelling and shrinkage) and suitability for decoration; additionally, it can be used in other industries (Ratnasingam et al. 2010). A correct drying operation stabilizes wood dimensions, improves mechanical properties, and protects them from biological attacks by reducing the moisture content to desirable values. However, the methods currently being used, such as the use of solar energy and hot air energy, have drawbacks in terms of drying time. Moreover, the quality of the workpiece, which depends on the traditional baking process, is affected due to the delay in heat transfer during the traditional drying process, which generates heat from the work surface toward the core material and results in damage to the work surface from overheating (Hansson and Antti 2003, 2006; Ratnasingam et al. 2010). By contrast, the alternative drying process, which uses microwave energy for drying, can evenly distribute heat throughout the workpiece due to the interaction between the electromagnetic field and the entire workpiece. This is a fast and instant process and therefore has the advantage of a shorter duration when compared to traditional drying methods. Additionally, the quality of the workpiece is improved, as the work surface reaches a very high heat but distributes that heat throughout the work. There are many methods of drying with microwave energy. Using microwave energy with hot air throughout the drying process can reduce the drying time more than when drying with only hot air; however, there have been observations about deformation in the structure after drying with heat. Another study presented

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a microwave drying process with hot air, defined as a hybrid system, which turns on microwave or infrared power to help in the drying phase to reduce the effects of heat on the workpiece (Kowalskii and Rajewska 2009; Chena et al. 2019; Lv et al. 2017).

The drying process of planks using superhot air and steam to improve the drying performance was studied by researchers such as Johansson et al. (1997) and Dubey et al. (2016). Kowalskii and Rajewska (2009) studied the effectiveness of microwave hot air drying and infrared radiation to reduce the drying time associated with maintaining the final quality of the product. Holtz et al. (2010) studied the average energy efficiency of microwaves with hot air for drying. In addition, the breakthrough of the use of microwave-assisted heating in wood was developed by Rattanadecho (2006), who created a 2D mathematical model to study the phenomena occurring during the wood drying process using microwave energy as a heater within a pipe, i.e. a rectangular wave (rectangular wave guide). Vongpradubchai and Rattanadecho (2009) studied the phenomenon of drying wood using microwave energy while using a conveyor belt. This study examined the effectiveness of microwave energy to maintain high product quality and advances in a shortened drying time with volumetric (bulk) heating, as confirmed by Henin et al. (2014) and Ouertani et al. (2018). Furthermore, Prommas et al. (2012) analysed energy and exergy in the drying process of dry porous materials using a continuous microwave conveyor. By focusing on the drying phenomenon under the microwave drying process in the industry, Charoenvai et al. (2013) compared the product properties and specific energy consumption values in the use of microwave energy and microwave energy with hot air. Their research utilized the drying of plywood made from Durian peel.

Regarding the drying process, most of the researchers used traditional systems such as hot air drying, which is a less efficient system and takes a long time to dry. New research utilizes modern systems such as vacuum, microwave and infrared for drying; however, the parameters used as study criteria are not complete in all areas. In addition, the microwave system used in the experiment mostly works in batches (batch system). Moreover, the machine is just a prototype at the laboratory level—(laboratory-scale) only—and not a system used in real industry. This is a point that future studies need to consider when trying to determine an efficient alternative method of drying. Due to the multiposition microwave system and use of convection heat along with the continuous conveyor used in this research, the present method is a continuous flow system that can be used on a commercial scale. Thus, this method can be used for industrial applications. In the design of the drying process in this research, there is a combined system to dry rubberwood using the energy from the microwave together with hot air from the heater from the beginning to the end of the drying process. This hybrid system, which is a two-step drying process for rubberwood, involves a combination of the use of hot air at the initial stages of the drying process without turning on the microwave power system. After the specified period has elapsed, a microwave with hot air is turned on until the end of the drying process.

This research examined the heating process of a multiwave microwave feed system and continuous convection heating with a conveyor by studying information about the device-related working equipment, including the machine control procedures, to prepare for an experiment. The rubberwood drying process was studied by analysing parameters such as the drying rate, temperature of the rubberwood surface, percentage of moisture that decreased during the drying process and quality of the workpiece after drying in regard to its mechanical properties such as the internal wood strength and value of wood.

2 Materials and methods

2.1 Combined microwave drying system

Rubberwood drying experiments were carried out using a multiposition microwave and convection system with a continuous conveyor belt. This combined multifeed microwave-convection air and continuous belt system (CMCB) (Figs. 1, 2) has a working frequency of 2.45 ± 0.05 GHz, which has been used in wide-ranging industrial applications as assigned by the International Microwave Power Institute (IMPI) (Metaxas 1991). The microwave oven used in this study has a total of 12 air-cooled magnetrons, resulting in a maximum power of 11.2 kW; this power is suitable for continuously baking a large number of workpieces. This setup can also adjust the wave feed direction on the workpiece

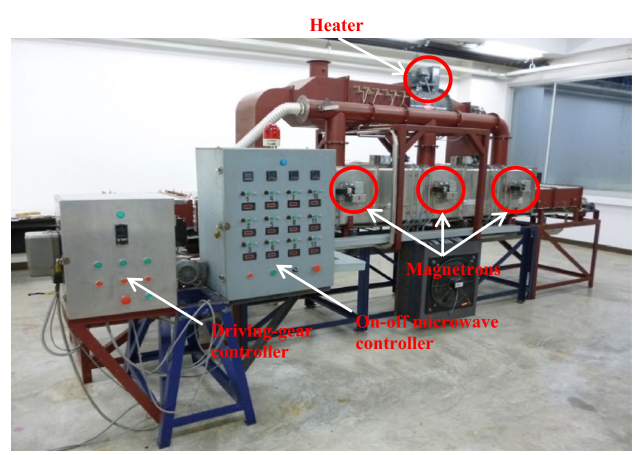

Fig. 1 Multi-feed microwave-convection hot air and continuous belt system (CMCB)

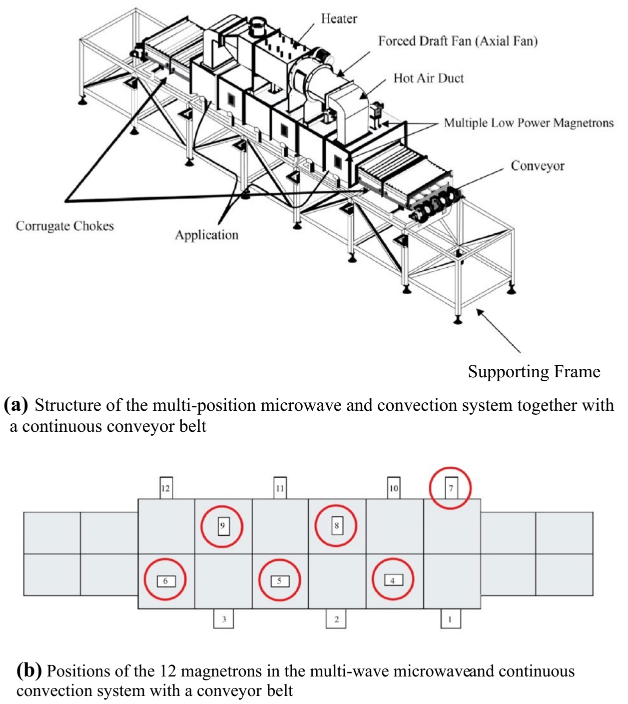

Fig. 2 Combined microwave drying system. **a** Structure of the multi-position microwave and convection system together with a continuous conveyor belt. **b** Positions of the 12 magnetrons in the multi-wave microwave and continuous convection system with a conveyor belt

by controlling the position of the 12 magnetons. The wave receiving period of the workpiece can be adjusted more or less by adjusting the speed of the belt, which has a belt conveyor speed of 2.0 m/min and passes through the oven via the conveyor to evaporate the moisture from the workpiece using the exhaust fan.

2.2 Sample preparation and drying experiments

In this paper, the kinetics of the drying process of rubberwood with dimensions of 5.0 cm wide × 2.5 cm thick × 30.0 cm long was studied using the multiposition microwave and convection system with a continuous conveyor system as a combined hybrid heating system and for conventional convective drying (hot air drying) to reduce the moisture content of rubberwood from 70% to an average of 20% (dry basis). Initially, the dry weight of rubberwood was determined by taking samples of rubberwood and drying it with a hot air dryer at a temperature of 103 ± 0.05 °C until the weight of the rubberwood was reduced to a constant value. Then, these data were used to calculate the initial moisture percentage. In each case, 22 pieces of fresh rubberwood that had not undergone any chemical processing or drying before the case were used. The variable used in the experiment was the temperature of hot air (an accuracy of ± 1.0 °C) in conjunction with the microwaves and drying methods of various systems. The details are explained in Table 1.

Rubberwood was then dried in various cases until the drying kinetics were known. During the drying process in the combined system, the temperature distribution on the rubberwood surface was examined using a thermo-infrared camera with an accuracy of ± 0.05 °C at various time intervals of 10, 30, 50, 70, 90, and 110 min. Sequentially, the suitable conditions of each process were evaluated, and the mechanical properties and energy used throughout the drying process were obtained. The physical properties of the rubberwood after drying—which could be initially evaluated in a visual manner, such as by twisting and cracking—using rubberwood with dimensions of 2.0 cm wide × 2.0 cm thick × 30.0 cm long under different processes, are shown in Table 2.

Table 1 Cases of the rubberwood drying experiments

Case	Process	Energy source	Conditions
1	Combined system[a]	Microwave energy + hot air	Microwave power with an ambient air temperature of 30 °C
2	Combined system	Microwave energy + hot air	Microwave power with an ambient air temperature of 50 °C
3	Combined system	Microwave energy + hot air	Microwave power with an ambient air temperature of 70 °C
4	Hybrid system[b]	Microwave energy + hot air	Microwave power with an air temperature 30 °C
5	Hybrid system	Microwave energy + hot air	Microwave power with a hot air temperature 50 °C
6	Hybrid system	Microwave energy + hot air	Microwave power with a hot air temperature 70 °C
7	Hot air drying[c]	Hot air	Hot air temperature of 50 °C and a relative humidity (RH) of 65 ± 1%
8	Hot air drying	Hot air	Hot air temperature of 70 °C and a relative humidity (RH) of 65 ± 1%

[a]Combined heat system using microwave energy together with hot air from the beginning of the drying process to the end of the process

[b]Hybrid system turned on at the ambient temperature of 30 °C for 30 min. After that, microwave energy is combined with the hot air until the end of the process

[c]Drying with hot air from the beginning of the drying process to the end of the process

Table 2 Drying experiments to reduce the external damage of rubberwood after drying

Case	Process	Conditions	Additional condition
1	Combined system[a]	Microwave power with an ambient air temperature of 30 °C	Not applicable
2	Combined system	Microwave power with an ambient air temperature of 30 °C	Reduce conveyor speed
3	Combined system	Microwave power with an ambient air temperature of 30 °C	Not applicable
4	Hybrid system[b]	Microwave power with a hot air temperature of 30 °C	Not applicable

[a]Combined heat system using microwave energy together with hot air from the beginning of the drying process to the end of the process

[b]Hybrid system turned on at the ambient temperature of 30 °C for 30 min. After that, microwave energy is combined with the hot air until the end of the process

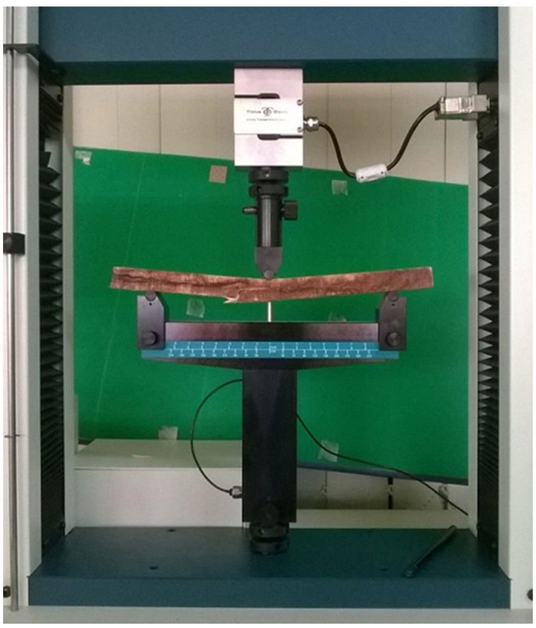

Fig. 3 Modulus of rupture (MOR) testing in tangential direction

2.3 Mechanical properties measurement

A static bending test was carried out in accordance with the British Standard (BS 373 1957) to determine the modulus of rupture (MOR) and modulus of elasticity (MOE), and ultimate force in axial direction, as shown in Fig. 3. The structure of the rubberwood was examined using a high-magnification microscope.

3 Results and discussion

Rubberwood was dried using a multiwave microwave feeding system and convection heating with a continuous conveyor in a combined heat system (hybrid system), and with hot air using a multimode microwave mode at a frequency of 2.45 ± 0.05 GHz with 6 magnetrons and a total power of 4800 W. The temperatures and moisture content at the rubberwood surface, drying time, and energy used to dry were analysed as follows.

Table 3 shows the duration and total energy used in the drying of rubberwood in the combined system, hybrid system, and hot air drying to reduce the moisture content of rubberwood from 70% to an average of approximately 20%.

Table 3 Energy consumption for drying rubberwood

Case	Process	Moisture (%)	Time (min)	Measured energy used (kWh)
1	Combined system at 30 °C	19.77	130	15.9
2	Combined system at 50 °C	19.99	120	18.0
3	Combined system at 70 °C	19.55	110	20.3
4	Hybrid system at 30 °C	17.32	150	16.3
5	Hybrid system at 50 °C	18.63	140	17.3
6	Hybrid system at 70 °C	18.22	130	20.5
7	Hot air drying at 50 °C	57.18	450	24.8
8	Hot air drying at 70 °C	56.78	450	46.6

According to the data in the table, drying rubberwood with microwave energy in the system and the combined heat and hybrid systems can decrease or shorten the drying time and energy consumption compared to drying with only hot air.

As indicated in Table 3, the minimum energy consumption of 16.3 kWh was obtained for hybrid system operated at 30 °C (ambient) for drying the rubberwood surface during the first 30 min and an ambient temperature of 30 °C together with microwave energy. The lowest energy consumption of only hot-air baking was 24.8 kWh, which took considerable time and energy to reduce the moisture in rubberwood. Both hot air temperatures—50 °C and 70 °C—reduced the moisture content to the same level, but in terms of energy consumption during drying, the use of hot air at 50 °C was found to consume less energy (24.8 kWh). In both cases, the drying time was 450 min, but the moisture could be reduced to 16.78. Thus, microwaves were found to cut drying times by one-third.

The experiments were performed using the microwave set to temperatures of 30, 50, and 70 °C to reduce the moisture from the initial moisture content of 70% to an average of 20%. A graph of the relationship between the temperature (left vertical y-axis) and moisture content (right vertical y-axis) at different drying times is shown in Fig. 4. From the experimental results, the drying of rubberwood using a CMCB reduces the moisture content from a 70% initial value (dry basis) to approximately 20%. Regarding the drying temperature, since rubberwood is a test material with a high initial moisture content before drying, during the first 30 min of drying, the temperature of the rubberwood surface (surface temperature) of all three cases tended to go in the same direction. The temperature increased rapidly. This high temperature occurred because of the presence of moisture content in rubberwood (Rattanadecho 2006; He et al. 2019). This property results in wood being able to absorb a large amount of microwave energy and efficiently convert it into heat energy. Moreover, when the drying period elapsed and the moisture of the rubberwood decreased, this property resulted in the ability of the rubberwood to absorb microwaves, resulting in temperature rise at a decreasing rate because heat accumulated inside the wood pieces, preventing the temperature of the surface of the rubberwood from dropping immediately. The temperature remained relatively stable for a period of time as the moisture transfer from the wood was constant. After that, it took approximately 80–100 min for the rubberwood to dry inside out and accumulate on and near the surface, causing the temperature of the rubberwood surface to increase again.

As shown in Fig. 4 (left vertical y-axis), when considering the influence of hot air temperature combined with microwave energy, it was found that during the first 30 min, the rubberwood surface had a high temperature consistent with the temperature of the hot air used However, over time, with the temperature of the rubberwood surface remaining constant, it was found that the use of microwave energy with a hot air temperature of 70 °C resulted in the rubberwood surface temperature being slightly lower than the use of microwave power at hot air temperatures of 30 and 50 °C. Due to the rapidly decreasing moisture content (see Fig. 4, right vertical y-axis) causing considerable water evaporation from the surface, this also resulted in substantial heat transfer out of the skin.

In terms of moisture percentage, the temperature of rubberwood increases dramatically during the first 30 min of drying from the absorption of microwave energy and converts it into heat, causing moisture to rapidly decrease. Considering the drying rate, this period is called the initial adjustment period (IAP). The moisture on the surface of rubberwood is still high. As shown in Fig. 4, the use of microwave energy combined with high hot-air temperature resulted in a stable drying rate period that was faster than when using a low hot-air temperature.

With regard to the drying rate of rubberwood in the combined heat system, a trend was found that corresponded to

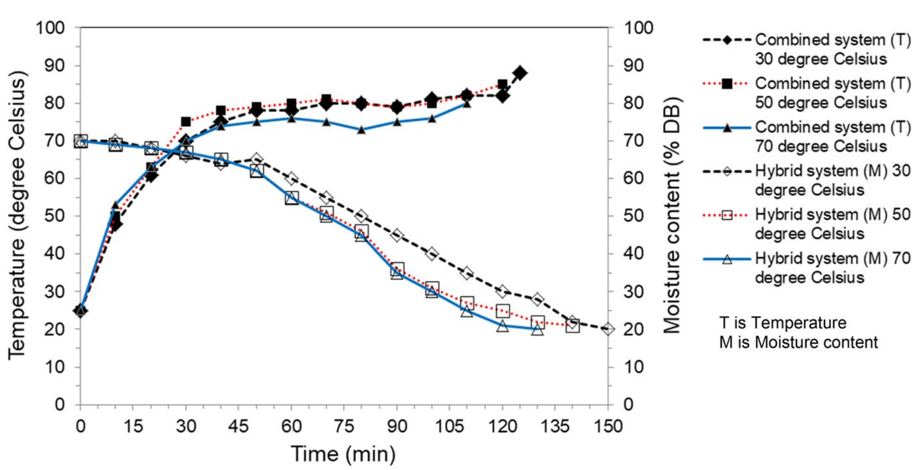

Fig. 4 Temperatures and moisture content at different drying times of rubberwood in the combined and hybrid systems

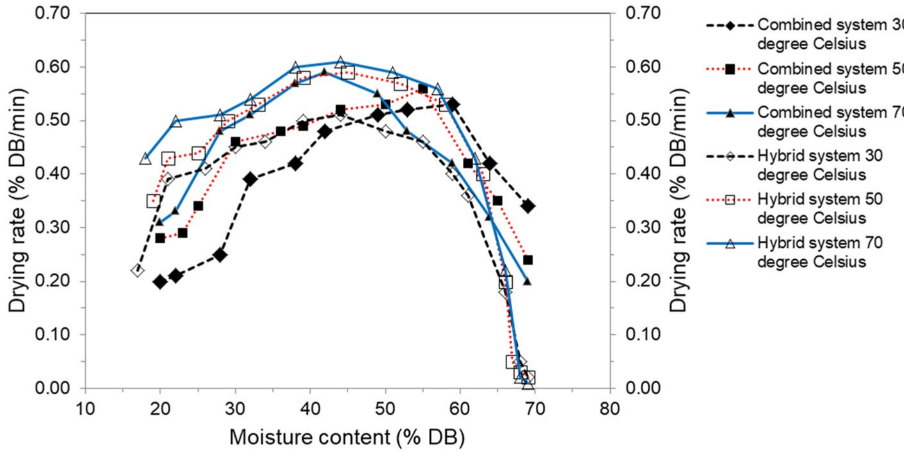

Fig. 5 Drying rates and moisture percentages when drying rubberwood in the combined heat system (combined system) for all 3 cases and hybrid system (hybrid system) for all 3 cases

the decrease in the moisture percentage of the rubberwood at the beginning of the period. The drying rate increased in the first 30 min, but after that, the drying rate entered a constant-rate period, which, in principle, is relatively stable and consistent throughout the period. However, Fig. 5 (left vertical y-axis) shows that there was an increase and decrease in the drying rate throughout the period. This result can be found clearly in the case of using microwave energy with hot-air temperatures of 30 and 50 °C for the drying process. A complex phenomenon occurred over time when moisture was transferred from the wood during the drying process. As a result, the ability to absorb microwave energy and change it to heat changed constantly. Therefore, the drying rate was not constant. However, the use of a high hot-air temperature (70 °C) showed that the drying rate was relatively high and more stable than when using a low hot-air temperature.

As shown in Fig. 5, it was found that the drying rate period had a rather consistent value. When compared to the drying of rubberwood in the combined heat system, only the first microwave energy phase with a hot-air temperature of 30 °C showed a rapid change in the drying rate. When the microwave was turned on, heat and moisture transferred quickly and continuously, making the drying rate quite high.

The microwave was turned on at temperatures of 30, 50, and 70 °C to reduce the humidity from an initial moisture content of 70% to an average of approximately 20%, and the data were recorded. The relationship between the temperature (left vertical y-axis) and drying time and the relationship between the moisture percentage (right vertical y-axis) and drying time (Fig. 6) are provided.

From the experimental results, drying rubberwood by hybrid system reduced the moisture from an initial value of 70% to an average of approximately 20% in all three cases. During the first 30 min, at an ambient temperature of 30 °C, rubberwood was first subjected to the hot-air temperature to remove some surface moisture. When turning on the microwave after 30 min, the temperature of rubberwood increased rapidly due to the presence of more moisture in the wood. After that, it took 100–110 min for the rubberwood to dry, resulting in the temperature of the rubberwood to increase again.

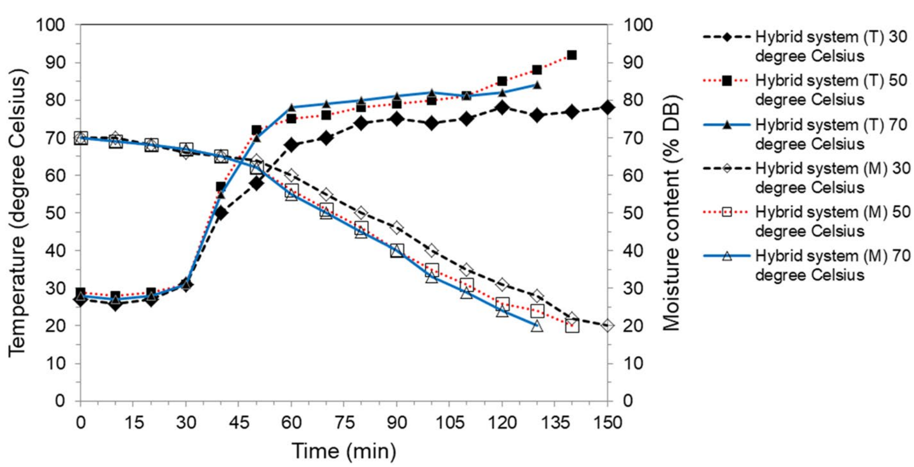

Fig. 6 Temperatures and moisture contents at different drying times of the rubberwood in the hybrid system for all 3 cases

According to Fig. 6 (left vertical y-axis), considering the influence of the hot-air temperature combined with microwave energy, during the first 30 min, the rubberwood surface area was similar to the ambient temperature. When turning on the microwave with hot air, it was found that the use of microwave energy with hot-air temperatures of 50 and 70 °C resulted in the temperature of the rubberwood surface becoming higher than when using microwave power with an ambient temperature of 30 °C.

In terms of moisture percentage, since the first 30 min of drying used only the ambient temperature of 30 °C, the surface moisture content of rubberwood was slightly reduced. However, this slight decrease was important, as the main aim was to expel moisture from the skin so that the rubberwood texture was more porous due to moisture gradient. The absorbed microwave energy could be converted into heat, causing the moisture to rapidly decrease during the 30–50-min time period, this period is called IAP. However, the moisture of rubberwood was still high, and the microwave energy began to convert and transfer into heat in the wood and entered the constant rate period from the 50th min onward. Then, the moisture transfer continued until reaching 120 min. Figure 6 (right vertical y-axis) shows that the use of microwave energy together with a hot-air temperature of 30 °C resulted in a decrease in humidity that is less than the use of hot-air temperatures of 50 and 70 °C. When considering an average moisture percentage of approximately 20%, it was found that the influence of hot air affects the drying time. For example, if the microwave was opened and a temperature of 50 and 70 °C was used to dry, this method was shorter than with an ambient temperature of 30 °C.

Regarding the drying rate of rubberwood in a hybrid system, it was found that there was a trend corresponding to the decrease in the percentage of moisture in the rubberwood during each period. That is the drying rate increased slightly in all three cases, but after opening the microwaves, there was a rapid increase in the drying rates. This result is comparable to the initial adjustment period and entering the constant rate period after the 50th min and onward.

For conventional drying experiment, the temperature was set at 50 and 70 °C to reduce the initial moisture content of 70% to an average of approximately 60%. Figure 7 (left vertical y-axis) presents the relationship between the temperature and drying time, and Fig. 7 (right vertical y-axis) presents the relationship between the moisture content and drying time. Convection heating reduced the moisture content in rubberwood from 70% to an average of approximately 60%, which is significantly lower than that with the microwave drying process incorporated. In both cases, the temperature of the rubberwood surface gradually increased at the beginning of the drying process until it reached 180 min. As evident in the case of 70 °C hot air, the surface temperature of rubberwood did not increase beyond the temperature of the hot air used in the drying process. Owing to convection where heat was fed only to the surface of the rubberwood, when drying for a period of time, the rubberwood surface was dry, but the moisture inside the wood remained because heat was not fully conducted. A temperature difference to cause heat transfer into the wood was required. This was different from drying with microwave energy, which caused the rubberwood to heat thoroughly from the inside. Therefore, this process required a long drying time, resulting in high energy consumption.

The drying time was found to be very long when using hot air alone for drying rubberwood. Temperatures of 50 and 70 °C did not yield very different rates of decreasing moisture content, with an average variation of only 1% compared to the hot-air temperature, as shown in Fig. 7 (right vertical y-axis). Moreover the drying rate was 25 times lower in conventional heating than when using microwaves in the combined heat and hybrid system, as shown Fig. 8. When drying rubberwood at a hot air temperature of 70 °C, the average drying rate was slightly higher than that of drying at a hot-air temperature of 50 °C.

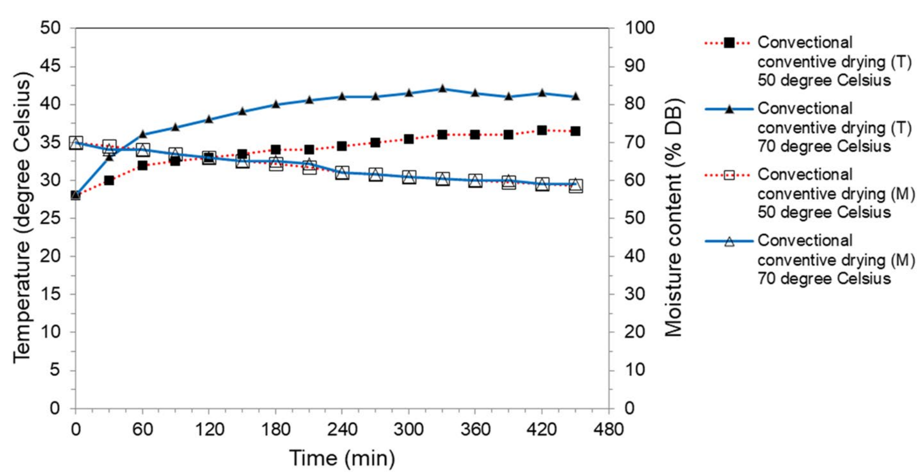

Fig. 7 Temperatures and moisture contents at different drying times of rubberwood with hot air in both cases

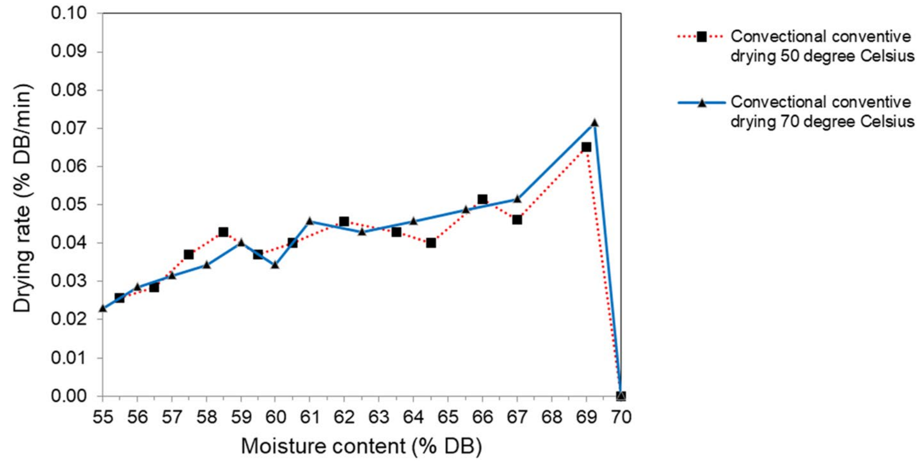

Fig. 8 Drying rates and moisture contents when drying rubberwood with hot air in 2 cases

3.1 Temperature distribution on rubberwood surface

Figure 9 shows the temperature distribution on the rubber wood surface during the drying process in the combined system after 10, 30, 50, 70, 90 and 110 min. In the first phase of the drying process, rubberwood absorbed microwave energy, and heat was generated around the edges and at the end of the rubberwood on both sides. As time went on, the distribution was consistent throughout the wood pieces, with the slowest heat generating point located at the bottom of the rubberwood. The temperature uniformity of the rubberwood was caused by the transfer of heat from the inside to the outside with the interaction between the rubberwood and the microwaves and the movement of the rubberwood on the belt. The wave feeding position allowed the material to be hit in many directions and caused the wave to be distributed widely throughout the area. Therefore, rubberwood received waves thoroughly in all areas.

3.1.1 Temperature field on the surface of samples under hybrid drying

The temperature distribution patterns on the rubberwood surface during the drying process in the hybrid system at 10, 40, 70, 100, 120, and 150 min are shown in Fig. 10. At the beginning, only a temperature of 30 °C (ambient) was required to first expel some of the moisture from the skin. The temperature distribution was found to be consistent throughout the wood pieces. Rubberwood had a temperature close to the temperature of the surrounding atmosphere. When microwaves were turned on at 30 min, the distribution pattern was similar to the case of the combined heat system. Rubberwood absorbed microwave energy, and heat was generated at the edges and end on both sides. As time went on, the distribution became even across the wood pieces.

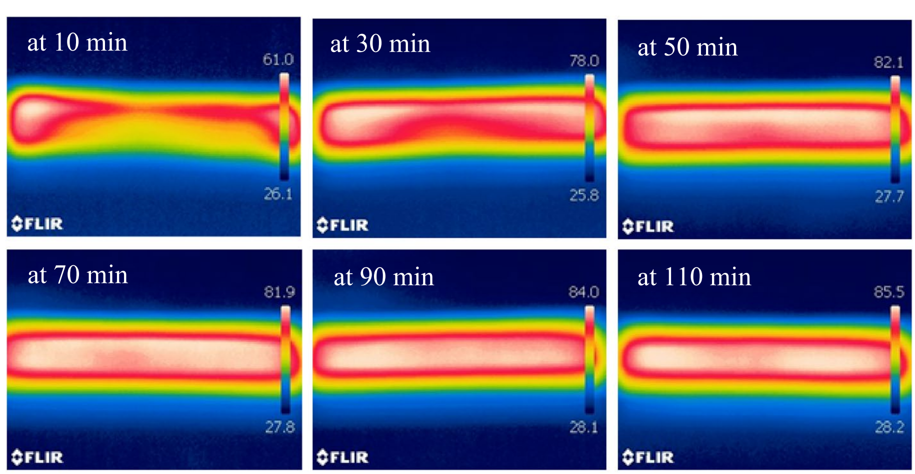

Fig. 9 Temperature distribution on the surface of the rubberwood subjected to combined heat (combined system) at various times

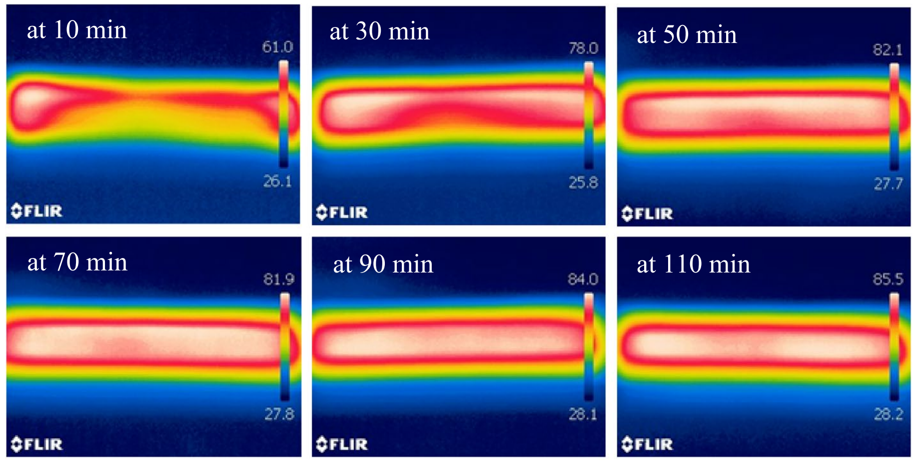

Fig. 10 Temperature distribution on the surface of the rubberwood in a hybrid system at various times

3.1.2 Temperature field on the surface of samples under hot air drying

The temperature distribution on the rubberwood surface during the hot-air drying process (50 °C) at various times of 30, 120, 210, 300, 390, and 450 min is shown in Fig. 11. The temperature first gradually increased to a moderate degree and remained relatively stable or slowly increased until the end of the drying process. When drying with hot air, the temperature distribution was uneven across the wood pieces. One side had a temperature higher than that of the other, as it was heated from the outside to the inside by hot air. This method resulted in a less thorough transmission of heat compared to uniform heating in wood pieces with microwave energy.

3.2 Mechanical properties of dried rubberwood

The duration and energy used throughout the drying process, including the physical properties of the rubberwood after drying such as twisting, cracking, and overall integrity, were evaluated initially by sight. Suitable cases were selected for use in the mechanical testing of wood as follows:

1. Combined heat system (combined system at 30 °C)
2. Hybrid system (hybrid system at 30 °C)
3. Drying using hot-air method (50 °C)

3.2.1 Modulus of elasticity (MOE) and modulus of rupture (MOR)

Twenty-two rubberwood samples for each specific test with dimensions of 2.0 cm wide × 2.0 cm thick × 30.0 cm long were subjected to the drying process in all three cases. Samples from all three drying methods were tested for mechanical properties using a bending test to obtain the modulus of rupture (MOR), modulus of elasticity (MOE) and the ultimate force as shown in Table 4.

The MOE, MOR, and ultimate force applied to all three cases indicated that rubberwood dried by microwave energy

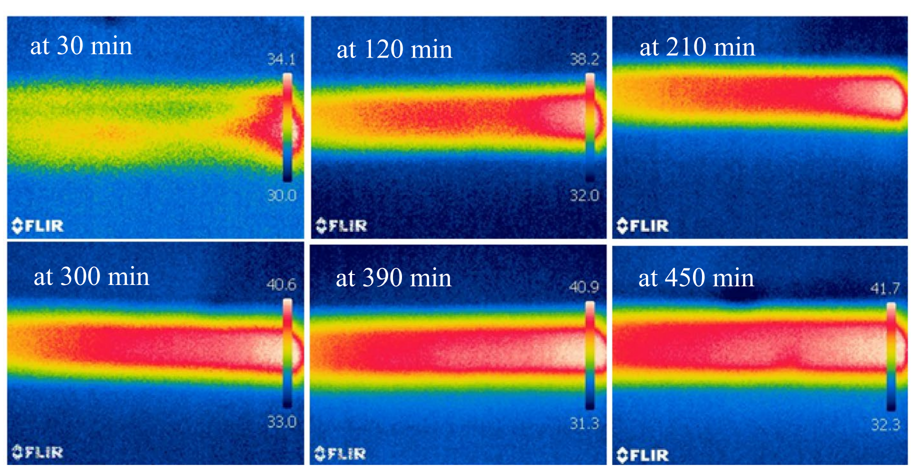

Fig. 11 Temperature distribution on the surface of rubberwood during hot air drying at various times

Table 4 Modulus of elasticity (MOE), modulus of rupture (MOR), and ultimate force applied to 3 cases

Process	MOE (MPa) (axial direction)		MOR (MPa) (tangential direction)		Ultimate force (kN) (axial direction)	
	Mean	COV	Mean	COV	Mean	COV
Combined system at 30 °C	5206	0.007	88.42	0.049	2919	0.001
Hybrid system at 30 °C	5404	0.002	97.34	0.069	3434	0.009
Hot-air drying at 50 °C	4643	0.004	88.43	0.027	2952	0.004

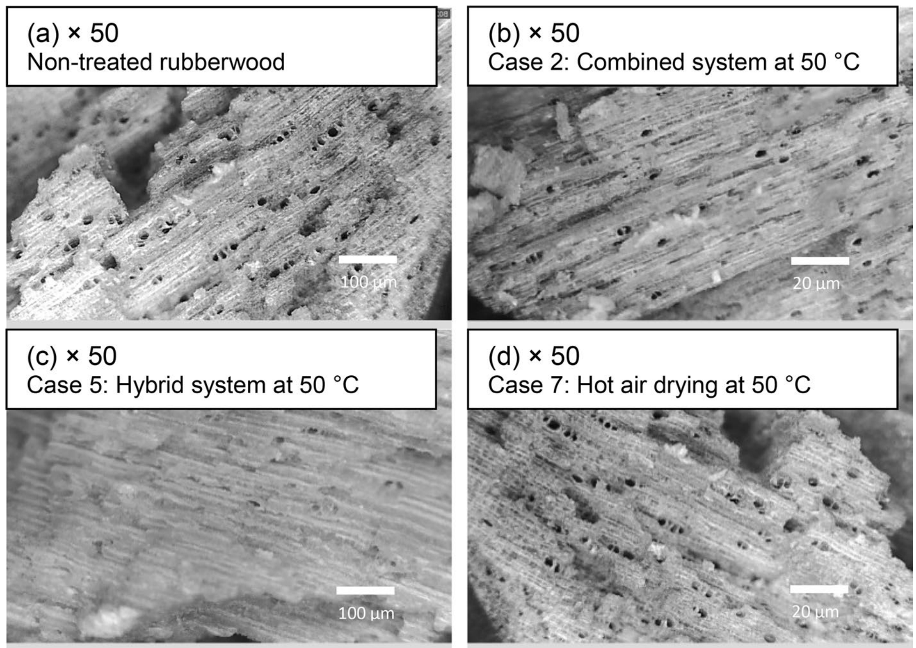

Fig. 12 Rubberwood structure of **a** non-treated rubberwood and rubberwood structure dried by **b** the combined process, **c** the hybrid process, and **d** the hot-air process

with the combined heat system and hybrid system resulted in rubberwood being similar to drying with hot air. Owing to the presence of a magnetron that emitted microwaves in many directions along with the directions and movement of the conveyor belt, the rubberwood thoroughly received microwaves. Heat was therefore conducted throughout the rubberwood, resulting in a low temperature difference in the wood. Highest mechanical properties were obtained in samples dried through hybrid system.

3.2.2 Microstructural characteristics

Drying rubberwood with combined system and hybrid system (hybrid system) caused no changes to the internal structure of the wood. After examing the pictures from a digital microscope (taken from the top at the same coordinate reference position as shown in Fig. 12), it can be observed that the structure of the pores in the wood keeps the same shape without any distortion or damage as the rubberwood was thoroughly microwaved. Heat was therefore generated throughout the rubberwood. The temperature difference was low. Therefore, the occurrence of thermal stress (heat stress) was reduced. This was different from drying with hot air. Hot-air drying deformed the internal structure of the wood which can be observed from the shape of the damaged porosity, as in Fig. 12d, which is consistent with the results of the mechanical property tests detailed in the previous section.

3.2.3 Evaluation of surface appearance of dried rubberwood samples

Considering the quality of the rubberwood that could be observed visually, it was found that the colour of the wood remained the same, and the shape of the wood experienced a slight contraction after drying due to shrinkage of rubberwood.

After drying the rubberwood with both the combined heat and hybrid systems, it was found that the quality of most pieces was good, and the pieces were similar in both colour and original shape, as shown in Figs. 13 and 14. The quality of the wood depended on the temperature of the hot

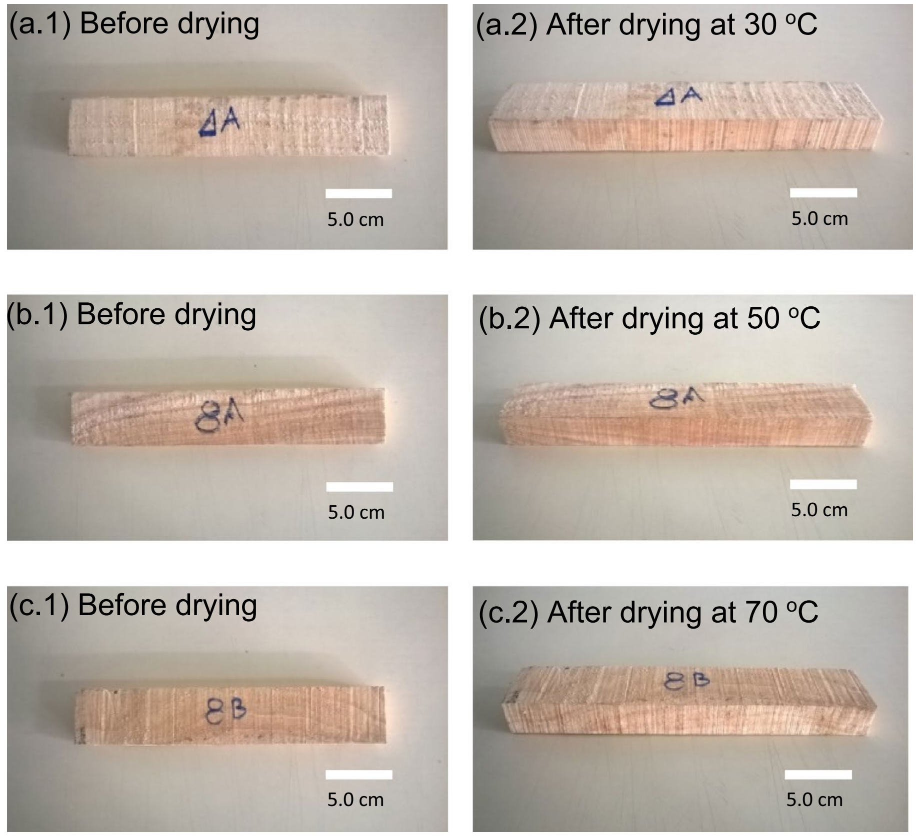

Fig. 13 Rubberwood after drying in the combined system with hot air at the following temperatures: **a** 30 °C, **b** 50 °C, and **c** 70 °C

Fig. 14 Rubberwood after drying in the hybrid system with hot air at different temperatures: **a** 30 °C, **b** 50 °C, and **c** 70 °C

air, which was different in each drying process, as opening the microwave with a high air temperature had a significant effect on the quality of the wood. In other words, the higher the hot-air temperature, the more likely the wood was to be deformed, warped, or split.

4 Conclusion

The results of rubberwood drying experiments using a microwave system with multi-position wave feeding and convection heat together with a continuous conveyor can be summarized as follows:

- The combined system reduced the moisture content from 70% to an average of approximately 20% within 110–130 min depending on the temperature of the hot air. Using this method, it was found that the minimum energy consumption for drying was 15.9 kWh, and the shape was also less distorted than that of drying alone with hot-air at temperatures of 50 and 70 °C.
- Hybrid system reduced the moisture content of rubberwood from 70% to an average of approximately 20% in 130–150 min depending on the temperature.
- Rubberwood dried by the hybrid system had the highest strength. The modulus of elasticity was 5,404 ± 12.8 MPa, the modulus of rupture (MOR) was 97.34 ± 6.7 MPa, and the maximum force was 3434 ± 31.7 N.
- Rubberwood after drying using the hybrid process was better than drying in the combined heat system.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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