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Comparative Evaluation on Product Properties and Energy Consumption of Single Microwave Dryer and Combination of Microwave and Hot Air Dryer for Durian Peel Particleboards

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Abstract

In this study, the idea is to use alternative "green" based on renewable resources as a raw material so as to be the adhesive into space in order to decrease formaldehyde emission in Thailand's particleboard manufacturing industries. It was found that dried durian peel could be used to replace formaldehyde-based resin for particleboard manufacture. In addition, drying the durian peel particleboard reduces biochemical and microbiological degradation.

This paper presents the comparative evaluation on product properties and specific energy consumption of single microwave dryer and combination of microwave and hot air dryer for durian peel particleboards. Microwave in a continuous belt system, consists of twelve 800 watts 2.45 GHz coupled into the cavity wall inside the system. A rectangular microwave cavity of dimensions 45cm x 90 cm x 270 cm combined with hot-air generator having the maximum operating temperature at 240 ˚C was chosen. Particleboards from Monthong peel with dimension of 20 cm × 20 cm were manufactured. The physical (Density, Moisture Content and Thickness Swelling), mechanical property (Internal Bond, dielectric (Relative dielectric constant, Dielectric Constant and Loss Tangent) properties of end products were determined. In addition, Electron Structure using Scanning Electron Microscopy and thermal photograph of end products were also investigated.

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Keywords: Dielectric; Internal Bond; Scanning Electron Microscopy; Thermal Photograph

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1. Introduction

Agricultural waste utilization in building materials with energy conservation properties is one promising alternative to meeting the challenges of disposing agricultural waste and to adding economic value to such new building materials. Many research studies [1-9] experimented with various raw materials and processes with the main emphasis on finding the new materials with low thermal conductivity suitable for use in energy-saving buildings. A wide range of technologies have been employed to manufacture building materials from agricultural waste so as to reduce dependence on natural wood and substitute the building materials commercially available in the marketplace. Located in the tropical zone, Thailand can grow many kinds of fruits and therefore produces a huge amount of fruit peels annually. Furthermore, agricultural waste is anticipated to increase in the future, and if we are unable to efficiently dispose of the agriculture waste, it will lead to social and environmental problems. The goal is thus to use agricultural waste to manufacture energy-saving building materials with low thermal conductivity so as to reduce heat transfer into the building [5], thereby decreasing energy consumption of electrical appliances, e.g. air conditioner, inside the building. By so doing, not only is the operation cost of the business slashed but the environment is protected. Thermal conductivity and bulk density of certain fruit peels are shown in Table 1.

Table 1. Thermal conductivity and bulk density of certain fruits [8]

Types	Bulk density (kg/m^3)	Thermal conductivity (W/m.K)
Pineapple	660	0.1149
Rambutan	636	0.1031
Durian	472	0.0921
Young coconut	330	0.0779
Pummelo	670	0.1240
Mangosteen	580	0.1119

Reference [8] found that coconut coir and durian peel respectively have low thermal conductivity of 0.0779 W/m.K and 0.0921 W/m.K as shown in Table 1. Hence, [8] could be regarded as Thai inventors who innovated the material with low thermal conductivity produced from coconut coir and durian peel fibers. [9] produced durian peel particleboards using synthetic binders, i.e., Urea-Formaldehyde (UF), Phenol-Formaldehyde (PF), and Isocyanate. Formaldehye-based adhesives, such as UF and PF resins, currently dominate the wood adhesive market. However, formaldehyde, regarded by many as a toxic air contaminant, is a human carcinogen that causes nasopharyngeal cancer. Besides cancer-causing hazard, exposure to formaldehyde causes non-cancerous health problems, such as eye, nose, and/or throat irritation (Hashim et al, 2011). Furthermore, formaldehyde emission and its non-renewable nature have become a matter of increasing concern. Environmentally-friendly adhesives from renewable resources and free of formaldehyde therefore are now being developed to replace the UF and PF binders. However, the binderless particleboard has the general problem related to microbiological growth. Hence, drying is used to preserve binderless particleboard. Drying the product reduces biochemical and microbiological degradation. It is the complicate process involving heat and mass transfer between the material surface and its environment. Thermal drying in solids might be regarded as a result from two simultaneous action: a heat transfer process by which the moisture content of the solid is reduced and a mass transfer process that implies fluid displacement within the structure of the solid towards its surface. Motion depends on medium structure, moisture content and characteristics of the material. Moreover, the separation of vapor from solid depends also on external pressure and temperature distribution on the total area of solid surface and the moisture content of drying air. Provided that thermal drying occurs in slow rate at ambient conditions, thus drying plants are designed and developed in order to accelerate appropriate drying rates to supply the product is more heat those of ambient conditions [10].

The drying of particleboard is the most energy intensive and costly process in the particleboards industry. Conventional particleboard dryers function under the basis of convective heat transfer from circulating hot air to the surface of particleboard, followed by subsequent conductive heat transfer from the surface to the center of particleboard. These dryers require a considerable amount of energy and long drying times in order to obtain high-quality particleboards. Therefore, innovative particleboard drying methods have been researched and studied. Unlike conventional heating, where heat is applied externally to the surface of particleboard, microwave irradiation penetrates and simultaneously heats the bulk of the particleboard. When properly designed, microwave drying systems offer several advantages over several mechanical methods, including reduction of drying time, high energy efficiency, and improvements in product quality for various applications. Microwave drying of particleboard; however, has not been used to a larger extent in particleboard industries due to insufficient knowledge of the complex interaction between particleboards structure and drying process parameters [11].

Microwave drying is one of the most interesting methods for drying particleboards. The application of volumetric heating could decrease the gradients of temperature and moisture during drying, resulting in an increase in the rate of heat transfer in particleboard.

The objective of this study was to the comparative evaluation on product properties and specific energy consumption of single microwave dryer and combination of microwave and hot air dryer for durian peel particleboards.

2. The related theory

2.1 Drying with Microwave Energy [2]

In convective drying, dry air is used to take away surface water saturation from the dried sample; therefore, creating a pressure gradient between the surface and inner part, which causes moisture migration from inside the sample to the surface. In this process, the temperature gradient will enhance the ability of dry air to remove water from the surface and increase the moisture migration rate within the sample. However, there are many disadvantages with this method. Among these are low energy efficiency and lengthy drying time during the falling rate period. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced heat transfer. Unlike conventional heating, where heat is applied externally to the surface of the material, microwave irradiation penetrates and simultaneously heats the bulk of the material. During applied microwave energy, the resonance effect can occur inside the material, which results in the field distribution not having an exponential decay from the surface. In some cases the highest field strength and therefore power density, can actually occur in the center of the sample. This is caused by the interfere of waves reflected from the back side of the sample. This mechanism pushes moisture out of the product with great efficiency as the moisture content of the product decreases. When properly designed, microwave drying systems have several advantages over conventional mechanical methods, including reducing the drying times, high energy efficiency, and offer improvements in product quality.

2.2 Fundamental Equation of Heat Generation with Microwave [2]

Dielectric materials absorb and alter microwave to heat energy, which is called density of microwave power absorbed (Q) and relates to electric field and magnetic field. In analysis of dielectric intensity E is normally used to evaluate the microwave energy absorbed. Therefore, the microwave energy absorbed or local volumetric heat generation term can be defined as Eq. (1):

$$Q = \omega\varepsilon_0\varepsilon_r' E^2 = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r' (\tan\delta) E^2 \tag{1}$$

where E is the electric field intensity, dependent upon position; f is the microwave frequency, ω is the angular velocity of microwave, $\varepsilon' r$ is the relative dielectric constant which describe energy absorption, transmission, and reflection at the microwave electric field; ε_0 is the permittivity of air; and tan δ is the loss tangent coefficient that indicates the ability of the product to absorb microwave energy.

Corresponding to Eq. (1), in the case of the amount of impact of tan δ, a lack of specimen penetration by the microwave without heat generation lowered the loss tangent coefficient, thus decreasing its impact on the absorbed microwave energy and volumetric heating. However, this could change at higher temperatures depending on relevant variables such as specific heat capacity and the characteristics and size of the material.

When the materials is heated unilaterally, it is found that as the dielectric constant and loss tangent coefficient can vary, the penetration depth will be changed and the electric field within the dielectric material is altered. The penetration depth is used to denote the depth at which the power density has decreased to 37% of its initial value at the surface.

$$D_p = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1}{2}}} = \frac{1}{\frac{2\pi f}{\upsilon}\sqrt{\frac{\varepsilon_r'\sqrt{1+(\tan\delta)^2}-1}{2}}} \tag{2}$$

where Dp is the penetration depth, $\varepsilon'' r$ is the relative dielectric loss factor, and υ is the microwave speed. The penetration depth of the microwave power is calculated according to Eq. (2), which shows how it depended on the dielectric properties of the material. It is denoted that products with huge dimensions and high loss factors may occasionally overheat a considerably thick layer on the outer layer. To prevent such phenomenon, the power density must be chosen; thus, enough time is provided for the essential heat exchange between the boundary and core. If the thickness of the material is less than the penetration depth, only a fraction of the supplied energy will be absorbed. Furthermore, the dielectric properties of particleboard specimens typically showed moderate loss depending on the actual composition of the material. A greater amount of moisture content revealed a grater potential for absorbing microwave. For all particleboard specimens, a decrease in the moisture content typically decreased $\varepsilon'' r$, accompanied by a slight increment in Dp.

2.3 Specific Energy Consumption (SEC)

Specific energy consumption (SEC) equation is represented by:

$$SEC = \frac{\text{Total electrical power supplied in drying}}{\text{Amoumt of water removed during drying}}, \left[\frac{kW - hr}{kg}\right] \tag{3}$$

where P total is a total electrical power supplied the in drying process; this term can be calculated from:

$$P_{total} = P_{mg} + P_{heater} + P_{exfan} + P_{cofan} + P_{con} \quad ,[kW \times 3600s] \qquad (4)$$

where Pmg is the electrical power supplied in the magnetron, P heater is the electrical power supplied in the heater, P exfan is the electrical power supplied in the exhaust fan, P blfan is the electrical power supplied in the blower fan, P cofan is the electrical power supplied cooing fan, and Pcon is the electrical power supplied in the conveyor.

3. Experimental setup

3.1. Particleboard prepartation

The specimens were prepared by first weighing durian peel fiber, durian peel powder and water according to the ratios in Table 2 and mixing well. The blended particles were gradually, manually placed layer-by-layer into a 250 mm x 250 mm mould to form the final mats which were then pressed at a platen temperature of 150 ºC. Pressure of 1000 - 1500 psi was applied to the boards. After the hot pressing, the boards were dried for 24 h to completely cure before being trimmed and cut into test specimens.

Table 2. Mixing Ratio (Fiber: Powder: Water) and Drying temperature

Board	Mixing Ratio (Fiber:Powder:Water) and Drying Temperature
1	1:1:1
2	1:1:1.5
3	2:1:1.5
4	2:1:2

Fig 1. Binderless particleboard from durian peel

3.2. Microwave-convective air drying at RCME [12]

Microwave-convective air drying was carried out using a combined multi-feed microwaved-convective aire and continuous belt system (CMCB). The Shape of the microwave cavity is rectangular with a cross-sectional area of 90 cm x 45 cm x 270 cm. The dried was operated was operated at a frequency of 2.45 GHz with maximum working temperature of 180 °C. The microwave power was generated by means of 12 compressed air-cooled magnetrons. The maximum microwave capacity was 9.6 kW with a frequency of 2.45 GHz. The power setting could be adjusted individually in 800 W steps. In the continuous processing equipment, two open ends are essential, in with the material is to be heated up on the belt conveyer where it was put in and taken out. In this equipment, leakage of microwaves was prevented by the countermeasure in duplicate with a combination of mechanical blocking filter (corrugate choke) and microwave absorber zone filter was provided at each of the open ends. The microwave leakage was controlled under the DHHS standard of 5 mW/cm^2. The multiple magnetrons (12 units) were installed in an asymmetrical position on the rectangular cavity. The microwave power was then directly supplied into the drier by using waveguide. An infrared thermometer (located at the opening ends) was used to measure the temperature of the specimens (accurate to ± 0.5 °C. The magnetrons and transforms used in this system were cooled down by a fan. In the continuous heating/drying equipment, two open ends were essential to feed in and feed out the product, through which the material to heated up on the belt conveyer was arranged in certain position. The belt conveyor system consisted of a drive motor, a tension roller, and a belt conveyor. During the drying process, the conveyor speed was adjusted to 0.54 m/min (at the frequency 40 Hz) and the motor speed was controlled by the VSD control unit. Hot air was generated using int 24 units of electric heaters with the maximum capacity of 10.8 kW and the maximum working temperature of 240 °C. The hot air was provided by blower fan with 0.4 kW power through the air duct into the cavity. The hot air temperature was measured using a thermocouple. For combination of microwave and hot air dryer drier, hot air was varied from 40, 50 and 60 °C for comparing to single microwave process.

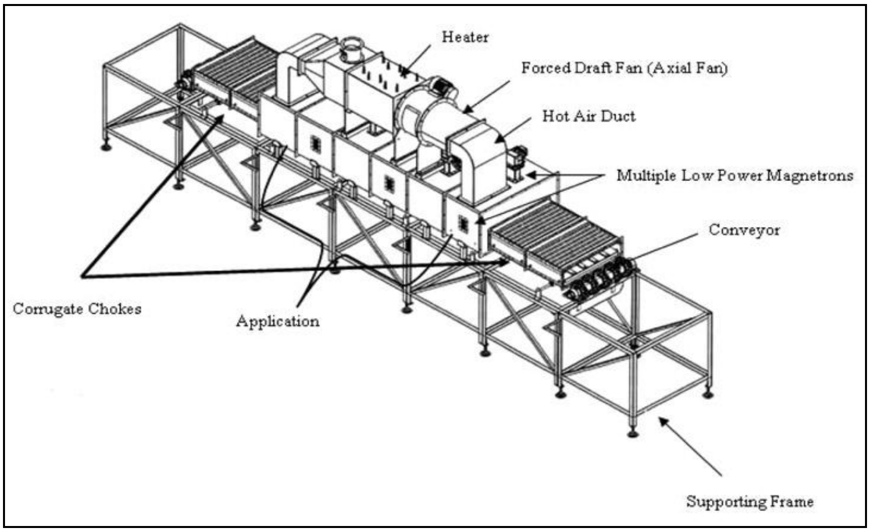


Fig 2. Schematic diagram

3.3. Specimen preparation for testing

After drying, testing of specimens was carried out according to JIS A 5908-2003 (Japanese Industrial Standards, 2003) for physical properties, i.e., density, moisture content, thickness swelling. Internal Bond of the particleboard was measure using Universal Testing (Testometric MICO 500). Thermal conductivity of the particleboards was measured using a thermal conductivity analyzer NETZSCH Model HFM 436 Lamda according to ASTM C 518 (American Society for Testing and Materials). Dielectric properties of particleboard were measured using Network Analyzer (PUSCHNER). The electron structure of particleboard was doned using Scanning Electron Microscopy (JEOL, SM-6510). Results show the comparative evaluation on product properties and specific energy consumption of single microwave dryer and combination of microwave and hot air dryer for durian peel particleboards.

4. Results and Discussion

Experimental data are analyzed to obtain the physical, mechanical and thermal properties of particleboard under various drying condition. The details of the analysis are as outlined in the following.

4.1. Specific Energy Consumption

Table 3 and 4 present the specific energy consumption in the single microwave and the combination of microwave and hot air dryer when drying durian peel particleboard. The electrical energy consumption during microwave convective air drying and convective drying of combined multi-feed microwave-convective air and continuous belt system is noted that the lowest specific energy consumption of 0.0926 MJ/kg is observed from the microwave-convective air drying method at air temperature of 60 °C. The reduction of specific energy consumption observed during drying and the reduction of drying time is achieved by increasing the hot air temperature level supplied to cavity. This causes the moisture content to decrease quickly. Therefore, microwave-convective air drying at hot air temperature of 60 °C can be used to efficiently dry the durian peel particleboard.

Table 3. Specific energy consumption in the single microwave

Power of Magnetron	Mixing ratio	SEC (MJ/kg)
4800 W	1:1:1	0.22012
	1:1:1.5	
	2:1:1.5	
	2:1:2	

Table 4. Specific energy consumption in the combination of microwave and hot air dryer

Power of magnetrons (W)	Hot air temperature	Mixing Ratio	SEC (MJ/kg)
2400	40	1:1:1	0.1129
		1:1:1.5	
		2:1:1.5	
		2:1:2	
	50	1:1:1	0.0968
		1:1:1.5	
		2:1:1.5	
		2:1:2	
	60	1:1:1	0.0926
		1:1:1.5	
		2:1:1.5	
		2:1:2	

4.2. Physical Properties

Density, moisture content and thickness swelling of the durian peel particleboard are carried out by two different drying methods; single microwave and combination of microwave and hot air dryer, as shown in Fig 3-5. No mark different is found between the methods with and without hot air supplied in cavity.

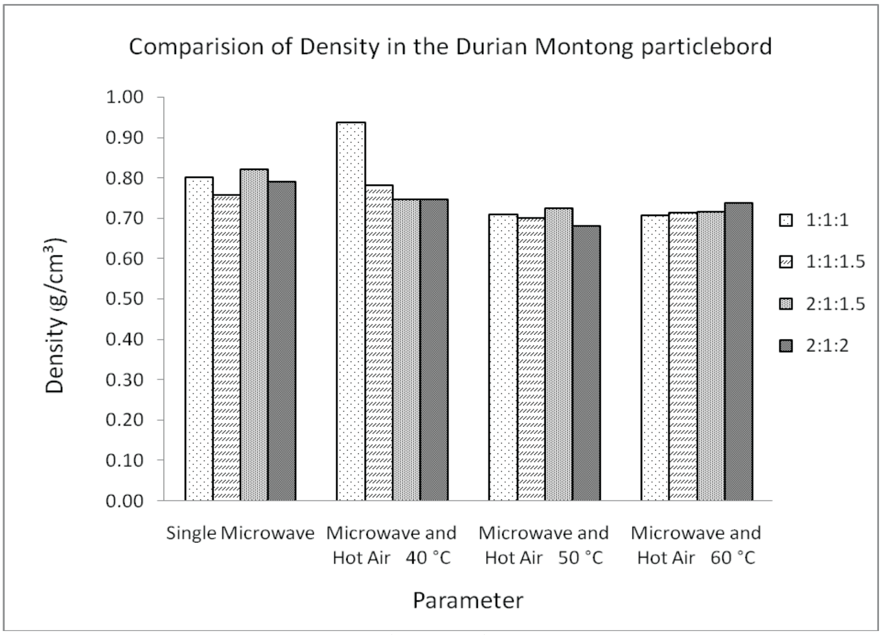


Fig. 3. Density

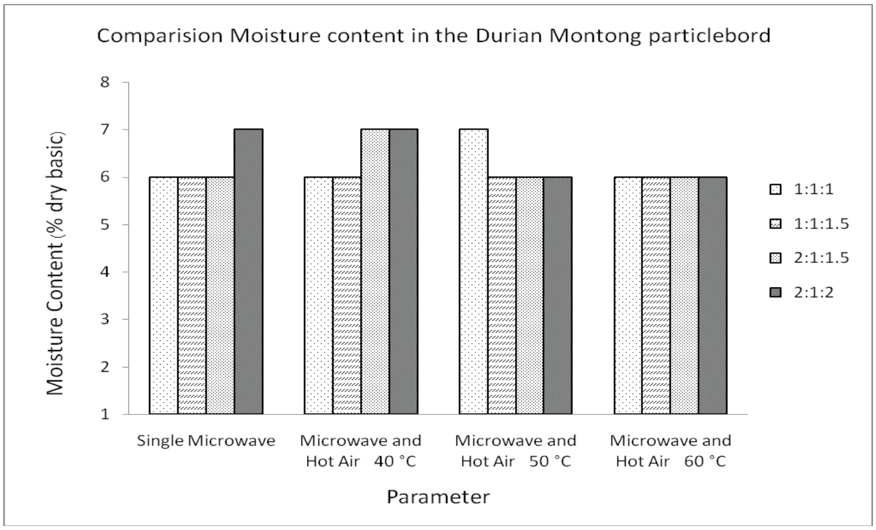


Fig. 4. Moisture Content

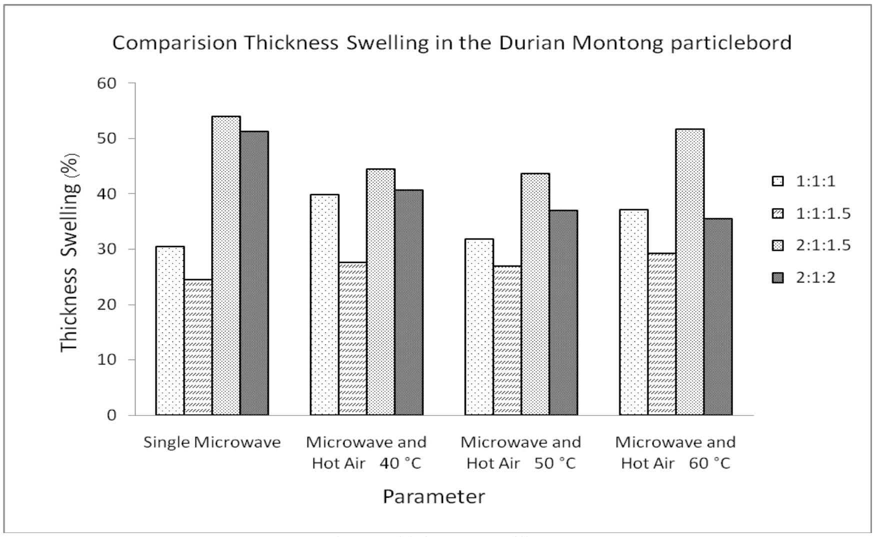


Fig. 5. Thickness Swelling

4.3. Mechanical Property

For mechanical properties, it was found that durian particleboards dried by the single microwave method have the best average internal bond properties as shown in Fig.6 . As a result, the centre of the sample, indicating the temperature at the sample core was higher than that at the surface. This is because microwave uniformly irradiated heat from the inside and there is more absorption of the microwave energy at the centre of the sample, resulting in temperature at the centre being higher than other area. Then, liquid in sample could be evaporated quickly causing vapour pressure high enough to migrate the moisture which was condensed to cover the entire surface. Thus, microwave drying obtain high quality mechanical property.

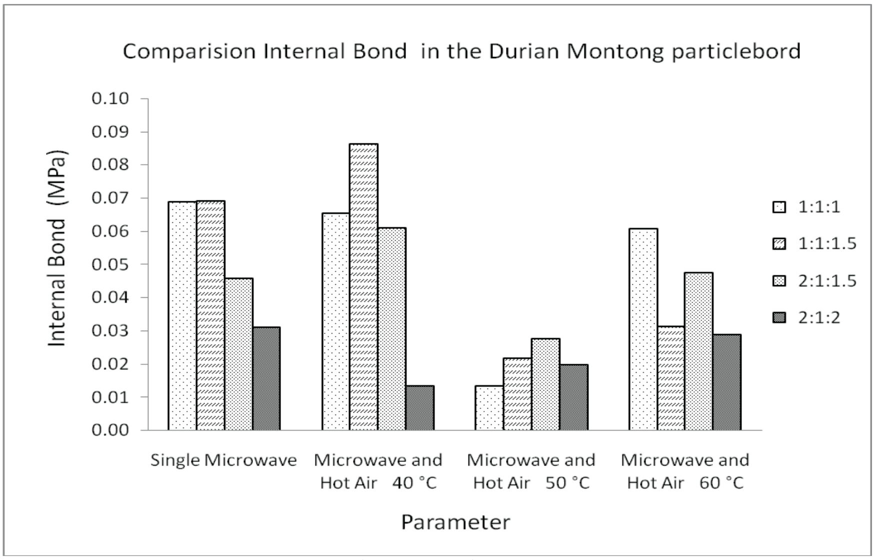


Fig. 6. Internal Bond

4.4. Dielectric Properties

Dielectric constant, relative dielectric constant and Dielectric loss tangent coefficient of the durian peel particleboard are carried out by two different drying methods; single microwave and combination of microwave and hot air dryer, as shown in Fig 7-9. No mark different is found between the methods with and without hot air supplied in cavity.

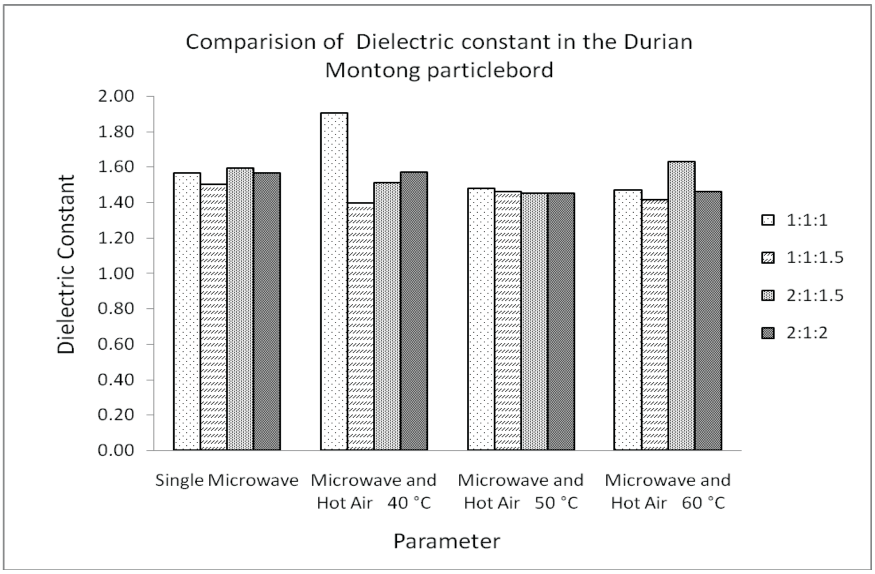


Fig. 7. Dielectric constant

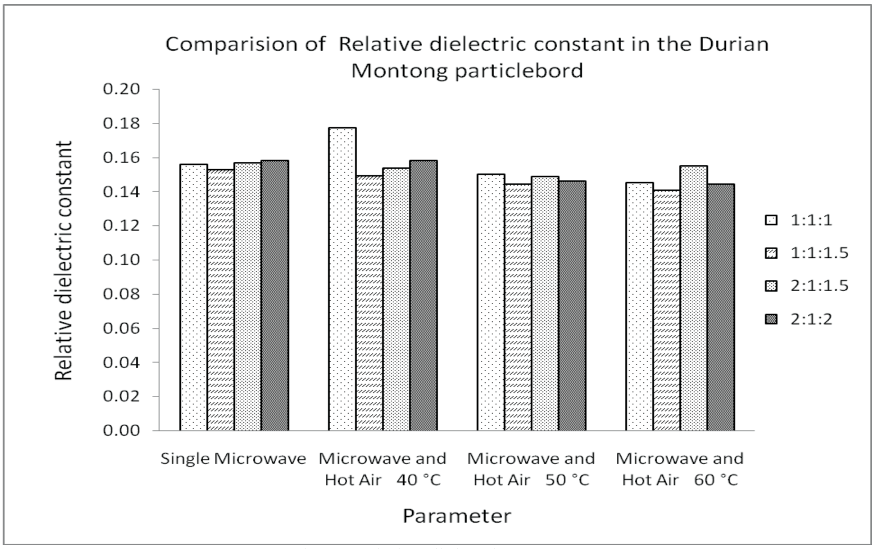


Fig. 8. Relative dielectric constant

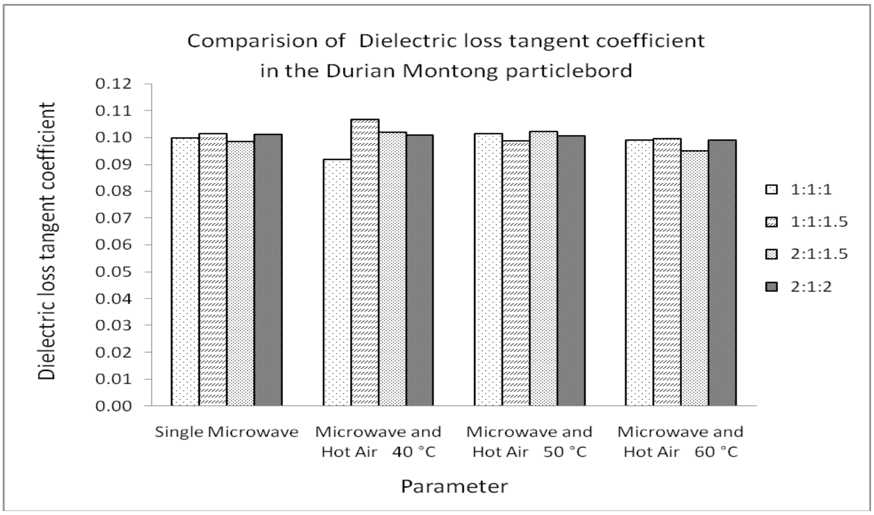


Fig. 9. Dielectric loss tangent coefficient

4.5. Microstructure of durian peel particleboard

In the following discussion, the internal structure of durian particleboard are investigated base on an analysis of the mechanical property; internal bond, after dyring. Table 5 and 6 present the texture (cross section and surface) overview of the durian particleboard specimen under various dried processes by using scanning electron microscopy (SEM) technique. It is found that the dried specimens in all cases seem to have a similar micro structure arrangement. However, the single microwave dried specimen has a better micro structure arrangement because of uniform energy absorption and less shrinkage. This leads to offer the mechanical property of dried product.

Table 5. The electron Structure (Cross Section) of Particleboard

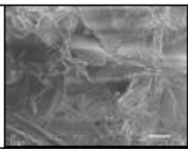
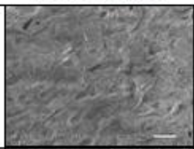
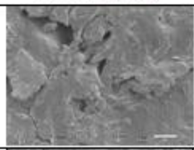
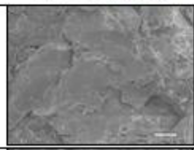
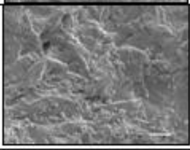
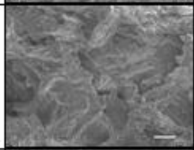
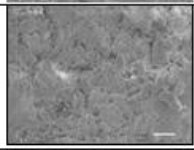
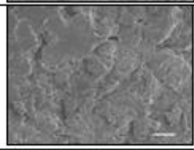
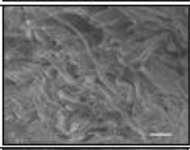
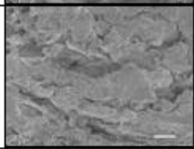
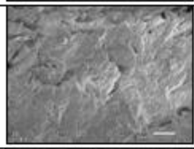
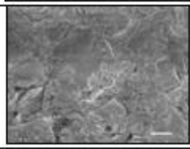
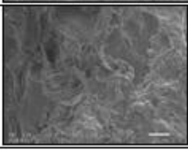
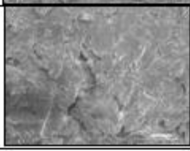
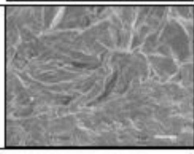
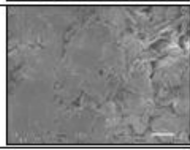
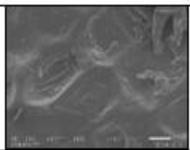
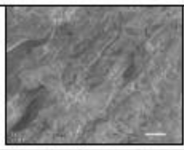
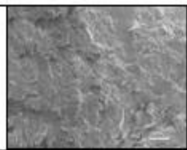
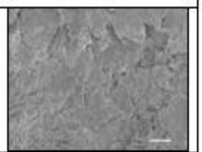
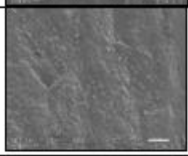
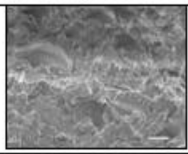
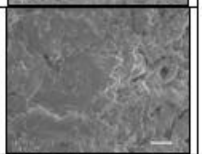
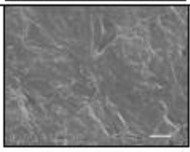
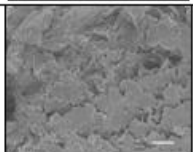
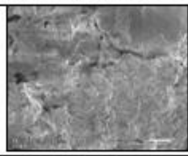
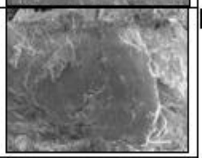
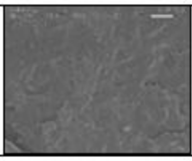
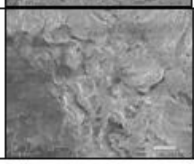
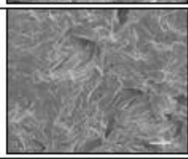
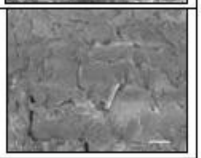
Candition	Single Microwave	Microwave and Hot Air 40 °C	Microwave and Hot Air 50 °C	Microwave and Hot Air 60 °C
1:1:1				
1:1:1.5				
2:1:1.5				
2:1:2				

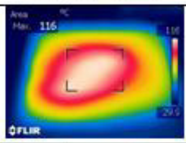
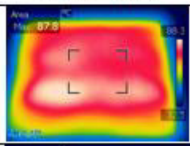
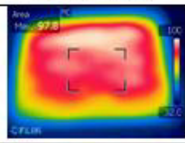
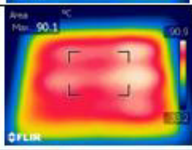
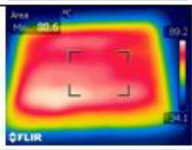
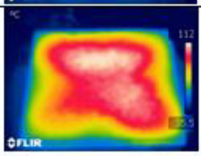
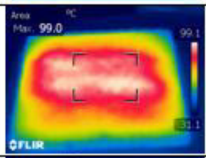
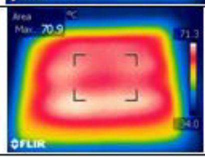
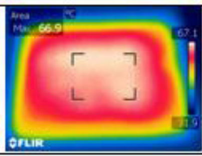
Table 6. The electron structure (Surface) of particleboard

Candition	Single Microwave	Microwave and Hot Air 40 °C	Microwave and Hot Air 50 °C	Microwave and Hot Air 60 °C
1:1:1				
1:1:1.5				
2:1:1.5				
2:1:2				

4.6 Thermo Photograph of durian peel particleboard

Thermo Photograph of durian peel particleboard (Drying time of 70 min) as shown in Table7. It is found that at high hot air temperature the temperature distribution of the sample continuously rises faster than that in the case of low hot air temperature. The reason is that in the case of high hot air temperature, convective drying is strong while the microwave energy is still supplied. When the drying time increases, the microwave power absorption is lowed because the moisture content decreases. This result is due to the influence of capillary pressure and vapour diffusion, which drives the moisture to the sample surface of durian particleboard sample. Near the end stage of the drying process as the moisture content inside the sample is reduced, the microwave power absorption decrease accordingly.

Table 7. Thermo photograph of particleboard (Drying time of 70 min)

Candition	Single Microwave	Microwave and Hot Air 40 °C	Microwave and Hot Air 50 °C	Microwave and Hot Air 60 °C
1:1:1				
1:1:1.5				
2:1:1.5				
2:1:2				

5. Conclusion

A combined multi-feed microwave-convective air and continuous belt dryer is one of the most interesting heating methods (requires lower energy consumption than single microwave system (SEC of 0.16509 MJ/kg) for the same or better product qualities than combined system. It shows the potential to reduce electrical energy consumption. Moreover, combined system permits quicker drying at high hot air temperature. If this technology is implemented to industry, it will decrease the production costs due to the lower electrical energy consumption.

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