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# COEFFICIENT OF THERMAL EXPANSION OF RUBBERWOOD (*HEVEA BRASILIENSIS*) IN CONVECTIVE DRYING PROCESS

**Kaung MT & Thanate R***

*Department of Industrial Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*

**thanate.r@psu.ac.th*

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Rubberwood drying is an energy-intensive process where drying defects are the main problems faced by the wood industry. The main objective of this study is to evaluate the coefficient of thermal expansion (CTE) of rubberwood to have a better understanding of the effect of temperature over the distortions of rubberwood during drying. Rubberwood samples were first dried at three different hot air temperatures and the mechanical properties of dried rubberwood samples were tested in the preliminary experiment to determine the suitable temperature condition for further evaluation of the CTEs of rubberwood samples. The CTEs of rubberwood in tangential and radial directions were evaluated through strain gages at three different moisture content (MC) levels: above 60%, at 12% and almost 0% (dry state). Based on the findings of this work, the CTEs of rubberwood in the tangential direction were found to have higher values than that of radial direction. The rubberwood samples had the highest CTEs values at 12% MC in both directions. Also, no significant differences were found between the experimental and expected CTE values of rubberwood as a function of specific gravity in the dry state.

Keywords: Rubberwood, coefficient of thermal expansion, strain gage, moisture content, specific gravity

## INTRODUCTION

Rubber tree (*Hevea brasillienisis*) has become a major economic plant in Southern Thailand as an important export commodity. This species has been cultivated for almost 25 years to produce latex before harvesting for different uses including furniture manufacturing. However, before utilisation, it is important to dry rubberwood lumber for its efficient and effective use for different applications (Umar et al. 2016). Drying is also an important process to carry out in timber production due to its energy and time-consuming characteristics (Oloyede & Groombridge 2000, Vongpradubchai & Rattanadecho 2009, Ratanawilai et al. 2015). In addition, wood swells or shrinks when it gains or loses moisture as it is such a hygroscopic material. Due to this natural behaviour of wood, the drying defects are the main issues of the drying process. As the wood dries below the fibre saturation point (FSP), it shrinks as well as drying stresses would develop during the process due to moisture content (MC) gradient and thermal variation in wood. These residual stresses are the major root cause of undesirable distortions of wood such as crooking, bowing and twisting which lead to the overall reduction of wood quality. In order to prevent drying defects, it is important to evaluate and understand the development of these residual stresses in wood. These stresses are often evaluated in an indirect way by means of dimensional changes of wood during drying.

It is a well-known fact that most materials change their dimensions as a function of temperature which is called thermal expansion (Cordero et al. 2009). The fractional change in dimensions of a material per unit rise in temperature is often characterised by the coefficient of thermal expansion (CTE) which is recognised as a fundamental parameter in mechanical and structural design applications of materials (Zeisig et al. 2002). Thermal expansion of wood can also be considered as an important factor in the wood drying process as temperature variations cause moisture flows in wood, and consequently hygroscopic deformations occur. Thermal expansion of wood is mostly positive in all directions. Nevertheless, according to Stamm (1935), wood has different CTE values (α) in

its radial (R), tangential (T) and longitudinal (L) axes. The CTE value in L direction is very small, ranging from 5–10 times less than that of T and R directions, and therefore, it is not often considered (Bergman et al. 2010). Earlier studies have paid much attention to the thermal expansion of various wood (Weatherwax & Stamm 1956, Kubler et al. 2007, Zhao et al. 2016, Goli et al. 2019). Weatherwax and Stamm (1956) measured the CTEs of a number of American wood species such as Sitka spruce, white fir and Douglas fir in the T, R and L directions, and it was reported that the CTEs have a linear relation with density. The investigation of CTEs of different wood species such as redwood, Douglas fir, yellow birch and red oak at different MC levels: above 60%, at 12% and at oven dry MC (dry state), was carried out by Kubler et al. (2007). It was concluded that the CTEs of wood were very heterogeneous as the coefficient of thermal expansion in tangential direction ($\alpha_t$) and coefficient of thermal expansion in radial direction ($\alpha_r$) were higher at 12% MC than those in dry condition. Additionally, Goli et al. (2019) calibrated the CTEs of Norway spruce in the R direction and obtained average $\alpha_r$ values, $30.9 \times 10^{-6}$ $K^{-1}$ at 7% MC and $31.8 \times 10^{-6}$ $K^{-1}$ at 11.4 % MC, respectively. Zhao et al. (2016) also evaluated the CTEs of green birch in the R direction and observed not only temperature variation, but the strong effect of wood MC on CTEs.

In measuring the CTE of materials, many researchers have successfully established numerous approaches such as dilatometry, optical heterodyne interferometry, digital image correlation (DIC) and strain gage measurement (Lanaz di Scalea 1998, Ratanawilai et al. 2003, Kubler et al. 2007, Cordero et al. 2009, Kulesh et al. 2009, Crawford et al. 2010, De Strycker et al. 2010, Wang & Tong 2013, Tang et al. 2014, Hou et al. 2016, Huang & Ying 2017). The dilatometry system generally consists of a tube thermal drive such as a furnace to heat the specimen and a push-rod connecting to the sensor to detect the displacement of the specimen. Although the dilatometry technique can be applied to measure the CTE of materials up to very high temperatures, its major weakness is the dilatometer which is a demanding task, and it cannot be performed on various types of geometries (De Strycker et al. 2010). Optical heterodyne interferometry has been effectively used to attain precision measurement for the CTE of materials (De Bona & Somá 1997, Cordero et al. 2009, Kulesh et al. 2009). However, the apparatuses required are considered extremely expensive for CTE determination of wood. The DIC is an image-based optical measuring technique and is often applied for sensing thermal deformation due to its relatively simple set up and non-contact feature. The DIC approach has no temperature limit, however, it usually encounters a convergence problem, particularly when the small strains are required.

Strain gage measurements have been extensively applied for mechanical tests of materials. The electrical strain gage is a universal measuring device and it can be applied to various types of matter and geometry. Compared to other approaches, the strain gage method is very cost effective and relatively easy to use. According to Tang et al. (2014), the results of thermal expansion of 304 stainless steel through strain gages were quite consistent with a data source from the National Institute of Standards and Technology, USA. In another study by Lanza di Scalea (1998), it was concluded that the strain gage approach was an efficient one for the characterisation of CTEs of anisotropic materials. De Strycker et al. (2010) also analysed the CTEs of stainless steel, measured by DIC and strain gage approach, and similar results were obtained below the temperature of 120˚C. Furthermore, Hou et al. (2016) observed that the experimental CTE results of asphalt concrete obtained by strain gages were in good agreement with the previously reported results. Ratanawilai et al. (2003) also revealed that consistent CTE measurements were obtained, compared to CTEs of printed circuit boards (PCBs) by moiré interferometry and strain gauges. All these preliminary researches have implied that the strain gauge approach is suitable in order to be economical and accurate for strain measurements of materials, as it requires less operation area. Therefore, the strain gage approach was preferable for strain measurement in this study.

Although previous studies had focused on the CTEs of various kinds of wood species, little data is available on the thermal expansion of rubberwood. Hence, this study aimed to evaluate the CTEs of rubberwood with the purpose of a better understanding of the important role of temperature variation in the deformation of rubberwood during drying.

## MATERIALS AND METHODS

### Materials

Rubberwood samples with no defects, used for furniture, with nominal dimensions of 25 mm in thickness, 80 mm in width and 1,150 mm in length were collected from a local rubberwood manufacturer in Songkhla province, Thailand. Redwood samples in dimensions of 30 mm thickness, 85 mm width and 1,150 mm length, and sentang samples in dimensions of 25 mm thickness, 80 mm width and 1,150 mm length were also obtained from the local wood factory. The wood samples were first saturated with a borax based chemical solution before drying. The aluminium (Al) samples (4 mm thickness, 10 mm width, 100 mm length) and copper (Cu) samples (1 mm thickness, 10 mm width, 150 mm length) were prepared for validation of strain gage approach.

### Methods and apparatus

In the present study, the rubberwood samples were dried in the laboratory-scaled designated hot air dryer and the mechanical properties of dried rubberwood samples were tested in preliminary experiments. The drying chamber has inner dimensions of 600 mm in width, 200 mm in depth and 1,500 mm in height. As hot air application, the chamber is connected to a hot air drying unit consisting of a 2 hp, 3,000 rpm blower, 3 kW electric heater and a valve. The blower is fitted with an electric heater by means of a 38.1 mm diameter pipe, and a K-type thermocouple was employed to detect hot air temperature. A 0.001 g precision load cell, integrated into a computer system, is placed on top of the chamber for continuous weight recording of the middle wood sample. The other samples were weighed by a digital balance at an accuracy of 0.01 g before and after each experiment. The MC was determined based on the weight loss of wood samples. Temperature profiles of wood samples were obtained through thermocouples positioned on the surface of the sample. The mechanical properties of dried rubberwood were tested through a universal testing machine. The CTEs of Al and Cu were also determined to calibrate the performance of proposed strain gage approach. The CTEs of rubberwood were then evaluated in the T and R directions by using strain gages. The specific gravity of rubberwood was also determined to differentiate between the experimental and expected CTE values of rubberwood at dry state condition. Moreover, in order to get more knowledge about the thermal expansion of wood, the measurements of the CTEs of redwood (*Xylia xylocarpa*) and sentang (*Azadirachta excelsa*) were conducted, as these two kinds of wood are widely used in Thailand for various purposes. The experimental setup with hot air dryer, universal data recorder (EDX-100A-4H) and bridge box (DBT-120A-8) for determination of the CTEs of wood is shown in Figure 1.

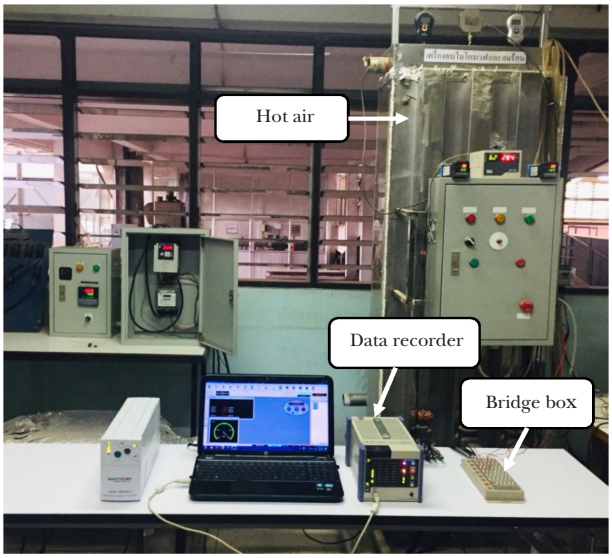


**Figure 1** Experimental set up for thermal expansion

### Drying conditions

The rubberwood specimens were dried using a drying chamber at hot air temperatures of 60, 80 and 100 °C to attain the targeted MC of 12%. The air flow was fixed at 2.5 $ms^{-1}$ throughout the whole process.

### Mechanical properties of dried rubberwood

For the mechanical properties of dried rubberwood samples, four types of testing, namely, compression parallel to the grain, compression perpendicular to the grain, tension perpendicular to the grain and static bending test were performed according to ASTM D143-14.

## Thermal expansion test

In order to gauge the validation of the proposed strain gage approach, the measurements of CTE were firstly repeated three times on the Al and Cu samples and the values obtained were averaged. Before the installation of strain gage, the samples were polished by sand tape and cleaned to make their surfaces smooth. The strain gage was then bonded to the surface of each kind of sample, and thermocouple was attached as close as possible to the gage to detect temperature profile of the sample during heating, as depicted in Figure 2a and 2b. The prepared Al and Cu samples were then heated in the oven at temperature 80 °C for one hour. The CTEs of Al and Cu samples were computed as follows:

$$\alpha = \frac{\varepsilon}{\Delta T} \quad (1)$$

where α is the coefficient of thermal expansion, ε is measured thermal strain value and ΔT is temperature changes from an initial reference temperature.

The CTEs of rubberwood sample were characterised three times in T and R directions through strain gages, as illustrated in Figure 3a. Before strain gage attachment, the surface of the wood sample was first polished and cleaned to make it smooth. As shown in Figure 3b, in the T direction, the two strain gages were bonded at two points on the front surface of the sample. With regard to R direction, as can be seen in Figure 3c, the two strain gages were also bonded at two points on the side surface of the sample. After gage installation, the resistances of strain gages were checked with a digital multimeter. The initial temperature inside the chamber was detected by the infrared temperature measurement instrument. The

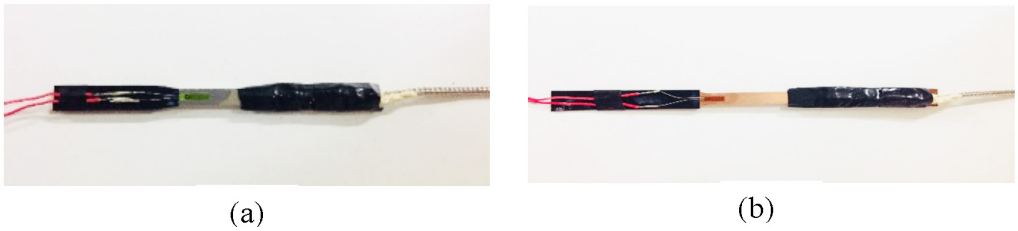


**Figure 2** Typical strain gage installation on (a) aluminum sample and (b) copper sample

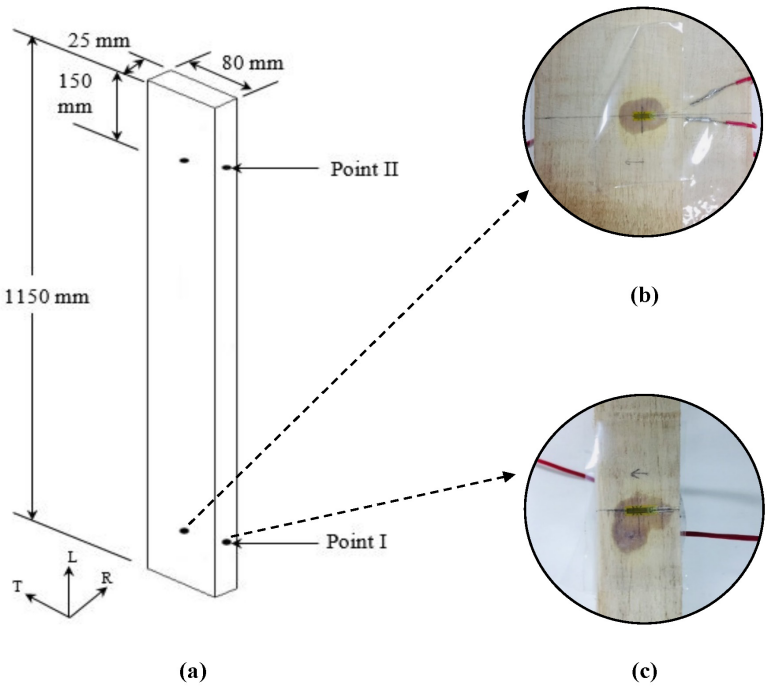


**Figure 3** (a) Location of strain gage attachment on rubberwood, (b) strain gage on the front surface (T direction) and (c) strain gage on the side surface (R direction)

rubberwood samples were then maintained in the chamber at hot air temperature of 80 °C. The CTEs of rubberwood sample were computed by equation 1.

Moreover, the specific gravity of rubberwood was also determined to evaluate the expected CTEs of rubberwood in oven dry condition. As according to ASTM 2395-14, the eight replicated of wood samples with dimensions of 25 mm thickness, 30 mm width and 100 mm length, were preferred to calculate the density of rubberwood by means of the test method of volume by measurement approach. Each sample was weighed and measured in three directions by a Vernier caliper at an accuracy of 0.01 mm. The samples were placed in the forced convection oven at temperature 103 ± 2 °C for 48 hours to obtain a theoretical MC of 0%. The density and specific gravity of samples were computed by:

$$\rho = \frac{m}{V} \quad (2)$$

$$G_o = \frac{\rho}{\rho_w} \quad (3)$$

where m is the weight of dried rubberwood, V is the volume of dried rubberwood, $G_o$ is the oven dried specific gravity, ρ is the density of rubberwood and $\rho_w$ is the density of water respectively. Then, $\alpha_t$ and $\alpha_r$ of rubberwood were calculated by the following equations (Bergman et al. 2010):

$$\alpha_t = (32.4G_o + 18.4) \times 10^{-6} \quad (4)$$

$$\alpha_r = (32.4G_o + 9.9) \times 10^{-6} \quad (5)$$

where $\alpha_t$ is the coefficient of thermal expansion in tangential direction and $\alpha_r$ is the coefficient of thermal expansion in radial direction.

Besides, the CTEs of redwood and sentang were also determined in the same procedure of the rubberwood samples for a better understanding on the vital role of temperature in wood drying and thermal expansion of wood.

## RESULTS AND DISSUSION

### Drying curve

Drying time of wood depends on its thickness and initial MC. However, these two are not important factors as drying curve of most wood does not reveal the constant-rate period (Simpso & Liu 1997). The reduction of the MC of rubberwood at three different hot air temperatures is presented in Figure 4. It took about 60 hours to reduce the MC from 90 to 12% with hot air temperature 100 °C. The targeted MC 12% was achieved in about 85 and 70 hours when the hot air temperature was maintained at 60 and 80 °C. Figure 5 shows the drying rate of three different drying conditions computed by the Moya approach (Moya et al. 2013). It was seen that the MC of wood had an effect on the drying rate. In the early stage of both conditions, the drying rate increased sharply when MC was above 50%, and then decreased slowly as the MC approached to an equilibrium level, as reported by Theppaya

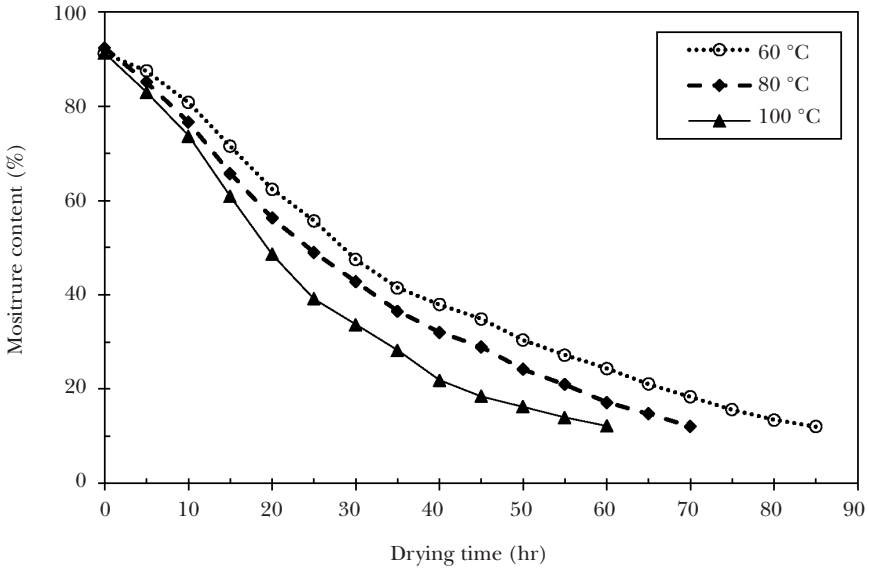


**Figure 4** Drying curves of rubberwood at three different hot air temperatures

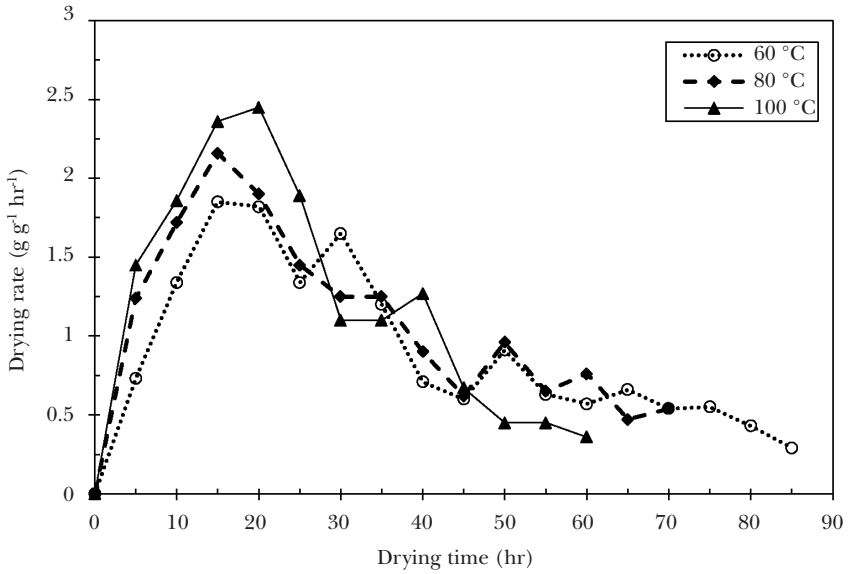


**Figure 5** Variation of drying rates with time at three different temperatures

and Prateepchaikul (2002) and Khamtree et al. (2019). This was because at above FSP, the MC of any size of the wood board decreases rapidly (Theppaya & Prateepchaikul 2002). The overall average drying rate was 0.9, 1.22 and 2.88% $hr^{-1}$, respectively, when the hot air temperature was kept at 60, 80 and 100 °C. High-temperature level reduced drying time significantly due to higher MC evaporation rates, as similarly reported by Kachaou and Maâlej (2000). On the other hand, higher temperature drying caused excessive physical defective samples.

## Mechanical properties of dried rubberwood

The ability of wood to resist load depends on several factors, including the type of load, direction, duration of loading and the presence or absence of defects such as knots and splits. Other factors such as ambient condition of MC and temperature can further influence the wood properties. The results of mechanical properties of dried rubberwood samples in regards to compressive strength parallel to the grain, compressive strength perpendicular to the grain, tensile strength perpendicular to the grain, modulus of elasticity (MOE) and modulus of rupture (MOR) are listed in Table 1. According to the analysis of Tukey's test, the compressive strength parallel to the grain values of dried samples at 80 and 100 °C were not significantly different from each other while the dried samples at 60 °C had low compressive strength value (p-value = 0.027). The compressive strength perpendicular to the grain value of dried samples at 60 °C was found to be lowest when compared to that of dried samples at 80 and 100 °C (p-value < 0.01). It was also observed that the dried samples at 80 °C had the highest tensile strength value of 2720.72 kPa (p-value < 0.01) while that of dried samples at 60 and 100 °C were 1881.75 and 1994.15 kPa, respectively. Following the static bending test, the average MOE values of dried samples at 60, 80 and 100 °C were 8571.76, 8893.35 and 8488.13 MPa, respectively, which were not significantly different from each other (p-value = 0.688). Nevertheless, the dried samples at 60 °C had the lowest MOR values of 53.74 MPa, while the other dried samples at 80 and 100 °C had MOR values of 66.26 and 61.97 MPa, respectively (p-value = 0.002).

Based on the results of drying conditions and mechanical properties of dried rubberwood, the hot air temperature 80 °C was chosen for further evaluation of the CTEs of rubberwood.

## Validation of the strain gage approach

During the heating process, strain values of Cu and Al samples increased linearly per unit rise in temperature per time. Figure 6 shows that the CTE values of Cu and Al samples, by mean of strain gages, were slightly varied at the start of the process, and then became almost stable until the end of the process. As displayed in Table 2, the overall average CTE values of Cu and Al were

**Table 1** Results of mechanical properties of dried rubberwood

| Property | Hot air temperature | | | p-value |
|---|---|---|---|---|
| | 60 °C | 80 °C | 100 °C | |
| Compressive strength parallel to grain (MPa) | 34.48[b] | 39.90[ab] | 42.03[a] | 0.027* |
| Compressive strength perpendicular to grain (MPa) | 14.67[b] | 17.80[a] | 16.91[a] | 0.000* |
| Tensile strength perpendicular to grain (kPa) | 1881.75[b] | 2720.72[a] | 1994.15[b] | 0.000* |
| Modulus of elasticity (MPa) | 8571.76[a] | 8893.35[a] | 8488.13[a] | 0.688 |
| Modulus of rupture (MPa) | 53.74[b] | 66.26[a] | 61.97[a] | 0.002* |

* = significant at $p < 0.05$, a & b = properties of samples, same alphabets denote not significant at $\alpha = 0.05$

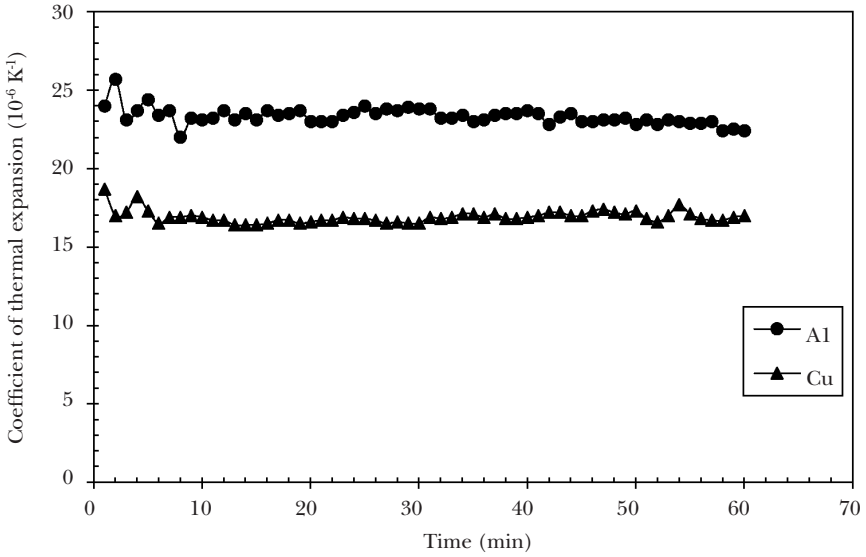


**Figure 6** Coefficient of thermal expansion of aluminum and copper samples

**Table 2** Average coefficient of thermal expansion of aluminum and copper samples

| Sample | Coefficient of thermal expansion, $\alpha \times 10^{-6}$ K$^{-1}$ | | |
|---|---|---|---|
| | Experimental value | | Reference value |
| | Average | SD | |
| Al | 23.2 | 0.1 | 23 |
| Cu | 17.1 | 0.3 | 17 |

about $17.1 \times 10^{-6}$ K$^{-1}$ and $23.2 \times 10^{-6}$ K$^{-1}$, respectively, which were very closed to the existing value of $17 \times 10^{-6}$ K$^{-1}$ and $23 \times 10^{-6}$ K$^{-1}$ from typical handbook (Touloukian et al. 1975). Based on the average CTE values of Cu and Al, it could be concluded that the proposed strain gage method has high accuracy for thermal expansion measurement of materials.

## Coefficient of thermal expansion of wood

Figure 7 demonstrates the temperature profile of rubberwood detected from two locations, as observed in Figure 3a, while the hot air temperature was 80 °C. It was noticed that $T_1$ was higher than $T_2$ as the lower part of the wood was first touched by the hot air. Strain values of rubberwood measured by two strain gages located in different points in the T and R directions are presented in Figure 8. The dimension of the sample responded slightly to the ambient temperature changes in the first few hours of the process, but as the process went by, it responded greatly. In both directions, the strain values were substantially increased until the peak point, followed by a gradual decrease. This may

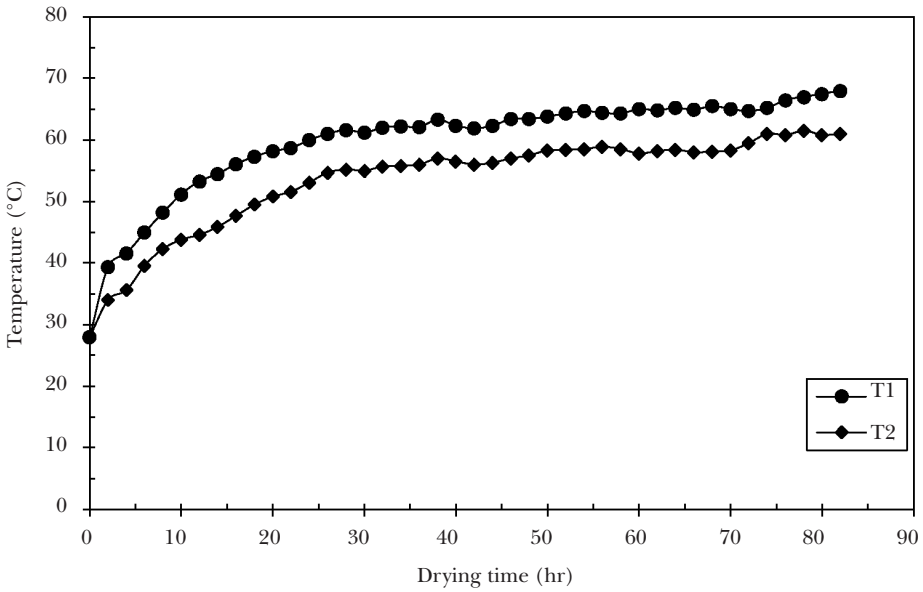


**Figure 7** Temperature profile of rubberwood detected from two locations

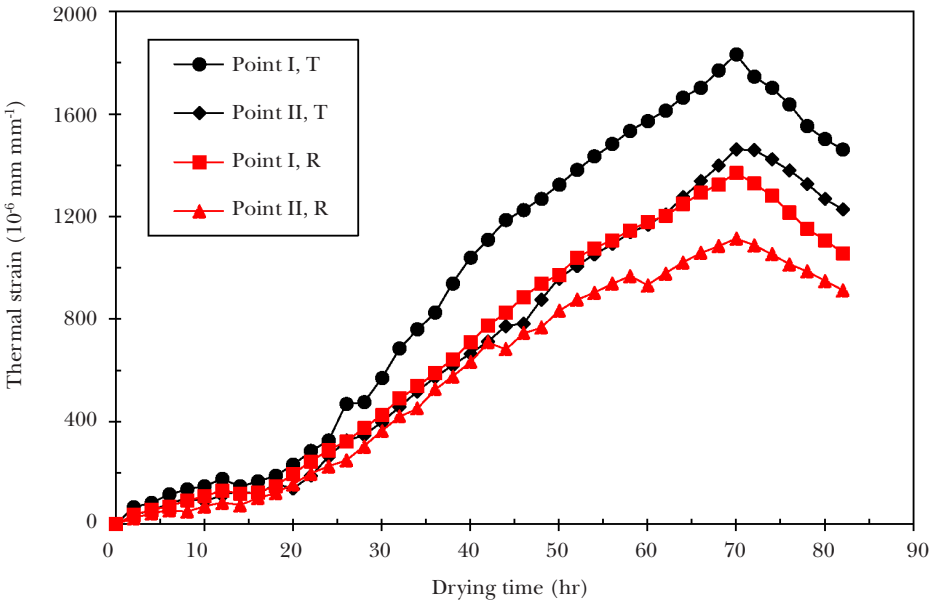


**Figure 8** Thermal strain values of rubberwood in tangential and radial directions measured from two locations

be attributed to the escape of all the free water in wood, causing a dimensional shrinkage of wood (Stamm 1935). However, in both directions, the strain values obtained from point I were greater than that from point II. This could be because of the non-homogeneous nature of wood and approximately 6 °C temperature difference between two points.

The CTE values of rubberwood in the T direction, calculated based on strain results from Figure 8, are plotted in Figure 9. Based on the calculated results from point I, the average CTE value of rubberwood stood at $6.3 \times 10^{-6}$ $K^{-1}$ when the MC of wood was above 60%, $49.5 \times 10^{-6}$ $K^{-1}$ when MC was at 12% and $36.5 \times 10^{-6}$ $K^{-1}$ when the wood was almost in dry condition. At point II, the average CTE value of rubberwood was $6.5 \times 10^{-6}$ $K^{-1}$, $48.9 \times 10^{-6}$ $K^{-1}$ and $37.2 \times 10^{-6}$ $K^{-1}$, when MC was above 60%, at 12% and almost zero, respectively. Thus, it could be concluded that in T direction, the evaluated CTE values from two locations were relatively similar to each other.

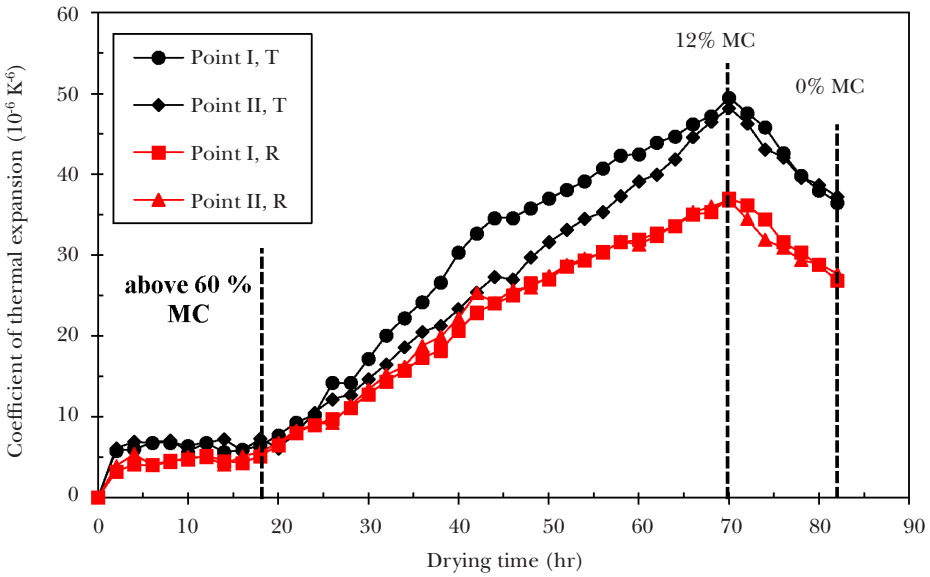


**Figure 9** Coefficient of thermal expansion of rubberwood in tangential and radial directions from two locations

The CTE values of rubberwood in the R direction, computed based on the results from Figure 8, are presented in Figure 9. At point I, the average CTE values were 4.4 × $10^{-6}$ $K^{-1}$, 37 × $10^{-6}$ $K^{-1}$ and 26.8 × $10^{-6}$ $K^{-1}$, respectively, for MC levels above 60%, at 12% and almost 0%, while the average CTE values obtained from point II were 4.6 × $10^{-6}$ $K^{-1}$, 36.8 × $10^{-6}$ $K^{-1}$ and 27.7 × $10^{-6}$ $K^{-1}$ at the three different MC levels: above 60%, at 12% and almost 0%. With regard to the R direction, the evaluated CTE values from two locations were also found to be comparable to each other.

The overall average experimental CTE results of rubberwood, redwood and sentang obtained from three repeated measurements are listed in Table 3. The results showed that wood had different CTE values at different MC levels, and it was clearly found that the MC of wood highly influenced the thermal expansion, as similarly reported by Ramiah and Goring (1965). Moreover, it was obvious that the CTE values of wood in the T direction were greater than that in the R direction. This was due to the dimensional changes of the wood specimens which were influenced by, not only its MC and temperature levels, but also its structure directions (Kubler et al. 2007). For example, $\alpha_t$ and $\alpha_r$ were 29 × $10^{-6}$ $K^{-1}$ and 24 × $10^{-6}$ $K^{-1}$ for Douglas fir in the dry condition, while 38 × $10^{-6}$ $K^{-1}$ and 38 × $10^{-6}$ $K^{-1}$ at 12% MC. The same for yellow birch where $\alpha_t$ = 28 × $10^{-6}$ $K^{-1}$ and $\alpha_r$ = 26 × $10^{-6}$ $K^{-1}$ in the dry state, while $\alpha_t$ = 37 × $10^{-6}$ $K^{-1}$ and $\alpha_r$ = 41 × $10^{-6}$ $K^{-1}$, respectively, at 12% MC. The expected values of rubberwood at dry state, $\alpha_t$ and $\alpha_r$, calculated by equation 4 and 5 with respect to $G_o$ of 0.595, were 37.7 × $10^{-6}$ $K^{-1}$ and 29.2 × $10^{-6}$ $K^{-1}$. Furthermore, the $\alpha_t$ and $\alpha_r$ values of redwood at dry state corresponding to $G_o$ of 0.77 were 43 × $10^{-6}$ $K^{-1}$ and 35×$10^{-6}$ $K^{-1}$, respectively. For sentang, with $G_o$ of 0.47, the $\alpha_t$ and $\alpha_r$ were 34 × $10^{-6}$ $K^{-1}$ and 25 × $10^{-6}$ $K^{-1}$, respectively. These values were closely matched with the values obtained through the experiment described in this study.

## CONCLUSION

In this study, the CTEs of rubberwood were measured in two directions, namely tangential and radial directions from two locations by employing strain gages to investigate the dimensional changes of wood and to get a better understanding of the role of temperature corresponding to the deformation of wood in the rubberwood drying process. The average values of $\alpha_t$ and $\alpha_r$ of rubberwood evaluated on three experimental replications were found to be heterogeneous. These average experimental values of $\alpha_t$ and $\alpha_r$ of rubberwood were relatively comparable with the expected values of $\alpha_t$ and $\alpha_r$, estimated with respect to the specific gravity of rubberwood. Therefore, it could be concluded that the proposed strain gage technique can be applied successfully for measuring the CTEs of rubberwood.

**Table 3** Average coefficient of thermal expansion of wood in tangential and radial directions

| Sample | Coefficient of thermal expansion, $\alpha \times 10^{-6}$ $K^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| | Tangential | | | Radial | | |
| | Moisture content | | | Moisture content | | |
| | Above 60% | 12% | 0% | Above 60% | 12% | 0% |
| Rubberwood | 6.6 | 48.5 | 37 | 4.5 | 38.1 | 27 |
| Redwood | 2 | 51.2 | 41.4 | 0.7 | 37.9 | 31.2 |
| Sentang | 10.4 | 42.5 | 31.2 | 7.2 | 36.5 | 23.3 |

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## REFERENCES

ASTM D143-14. 2014. *Standard Test Methods for Small Clear Specimens of Timber*. ASTM International, West Conshohocken, Pennsylvania. doi: 10.1520/D0143-14.

ASTM D2395-14. 2014. *Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials*. ASTM International, West Conshohocken, Pennsylvania. doi: 10.1520/D2395-14.

Bergman R, Cai Z, Calusen CA et al. 2010. *Wood Handbook: Wood as an Engineering Material*. U.S Department of Agriculture, Forest Service, Forest Product Laboratory, Madison, Wisconsin.

Cordero J, Heinrich T, Schuldt T et al. 2009. Interferometry based high-precision dilatometry for dimensional characterization of highly stable materials. *Measurement Science and Technology* 20: 095301. doi: 10.1088/0957-0233/20/9/095301.

Crawford G, Gudimettla J & Tanesi J. 2010. Interlaboratory study on measuring coefficient of thermal expansion of concrete. *Journal of Transportation Research Board* 2164: 58–65. doi: 10.3141/2164-08.

De Bona F & Somá A. 1997. Thermal expansion measurement of composites with optical heterodyne interferometry. *Experimental Mechanics 37:* 21–25. doi: 10.1007BF02328745.

De Strycker M, Schueremans L, Paepegem WV & Debruyne D. 2010. Measuring the thermal expansion of coefficient of tubular steel specimens with digital image correlation technique. *Optics and Lasers in Engineering* 48: 978–986. doi: 10.1016/j.optlaseng.2010.05.008.

Goli G, Becherini F, Tuccio MCD, Bernardi A & Fioravanti M. 2019. Thermal expansion of wood at different equilibrium moisture contents. *Journal of Wood Science* 65. doi: 10.1186/s10086-019-1781-9.

Hou TC, Huang SJ & Hsu C. 2016. A new approach for determination of the coefficient of thermal expansion of asphalt concrete. *Measurement* 85: 222–231. doi: 10.1016/j.measurement.2016.02.035.

Huang CY & Ying KC. 2017. Applying strain gauges to measuring thermal warpage of printed circuit boards. *Measurement* 110: 239–248. doi: 10.1016/j.measuremnt.2017.06.029.

Kechaou N & Maâlej M. 2000. A simplified model for determination of moisture diffusivity of date from experimental drying curve. *Drying Technology* 18: 1109–1125. doi: 10.1080/07373930008917758.

Khamtree S, Ratanawilai T & Nuntadusit C. 2019. An approach for indirect monitoring of moisture content in rubberwood (*Hevea brasiliensis*) during hot air drying. *Drying Technology*: 1–10. doi: 10.1080/07373937.2018.1563901.

Kubler H, Liang L & Chang LS. 2007. Thermal expansion of moist wood. *Wood and Fibre Science* 5: 257–267.

Kulesh VP, Moskalik LM & Sharoy AA. 2009. A heterodyne laser interferometer for dilatometer measurements. *Measurement Techniques* 52: 1319–1327. doi: 10.1007/s1101-010-9440-y.

Lanaz Di Scalea F. 1998. Measurement of thermal expansion coefficient of composites using strain gages. *Experimental Mechanics* 38: 233–241. doi: 10.1007/BF02410384.

Moya R, Urueña E, Salas C, Muñoz F & Espioza O. 2013. Kiln drying behavior lumber from ten fast-growth plantation species in Costa Rica. *Wood Material Science and Engineering* 8: 37–45. doi: 10.1080/17480272.2012.707686.

Oloyede A & Groombridge P. 2000. The influence of microwave heating on the mechanical properties of wood. *Journal of Material Processing Technology* 100: 67–73. doi: 10.1016/S0924-0136(99)00454-9.

Ramiah MV & Goring DAI. 1965. The thermal expansion of cellulose, hemicellulose and lignin. *Journal of Polymer Science Part C: Polymer Symposia* 11: 27–48. doi: 10.1002/polc.507110105.

Ratanawilai T, Hunter B, Subbarayan G & Rose D. 2003. A study on the variation of effective CTE of printed circuit boards through a validated comparison between strain gages and moiré interferometry. *IEEE Transactions on Components and Packaging Technologies* 26: 712–718.

Ratanawilai T, Nuntaduist C & Promtong N. 2015. Drying characteristics of rubberwood by impinging hot-air and microwave heating. *Wood Research* 60: 59–70.

Simpso WT & Liu JY. 1997. An optimization technique to determine red oak surface and internal moisture

transfer coefficients during drying. *Wood and Fibre Scince* 29: 312–318.

Stamm AJ. 1935.Shrinking and swelling of wood. *Industrial and Engineering Chemistry* 27: 401–406. doi: 10.1021/ie50304a011.

Tang K, Sha L, Li Y, Jin T & Liu S. 2014. Measurement of thermal expansion at low temperatures using the strain gage method *Journal Zhejiang University Science* 15: 323–330. doi: 10.1631/jzus.A1400051.

Theppaya T & Prateepchikul G. 2002. Parameters influencing drying behavior of rubberwood (*Hevea brasiliensis*) as determined from desorption experiment. *Drying Technology* 20: 37–45. doi: 10.1081/DRT-120002554.

Touloukian YS, Kirby RK, Taylor RE & Desao PD. 1975. *Thermal Expansion of Metallic Elements and Alloys*. 12: New York.

Umar I, Ashaari Z, Lee SH & Halis R. 2016. Oil-heat treatment of rubberwood for optimum changes in chemical constituents and decay resistance. *Journal of Tropical Forest Science* 28: 88–96.

Vongpradubchai S & Rattanadecho P. 2009. The microwave processing of wood using a continuous microwave belt drier. *Chemical Engineering and Processing: Process Intensification Process* 48: 997–1003. doi: 10.1016/j.cep.2009.01.008.

Wang YG & Tong W. 2013. A high resolution DIC technique for measuring small thermal expansion of film specimens. *Optics and Lasers in Engineering* 51: 30–33. doi: 10.1016/j.optlaseng.2012.08.001.

Weatherwax RC & Stamm AJ. 1956. *The Coefficient of Thermal Expansion of Wood and Wood Products*. US Department of Agriculture, Forest Service, Forest Product Laboratory, Madison, Wisconsin.

Zeisig A, Siegesmund S & Weiss T. 2002. Thermal expansion and its control on the durability of marbles. *Geological Society London Special Publication* 205: 65–80. doi: 10.1144/gsl.sp/2002.205.01.06.

Zhao L, Jiang J & Lu J. 2016. Effect of thermal expansion at low temperature on mechanical properties of Birch wood. *Cold Region Science and Technology* 126: 61–65. doi: 10.1016/j.coldregions2016.03.008.