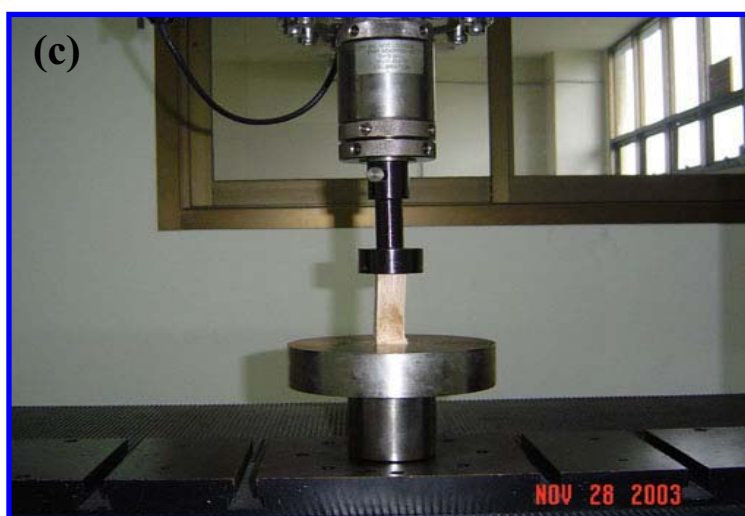




Figure 4.4: (a) Lloyd Universal Testing Machine. (b) Compression parallel-to-grain testing in progress. (c) Close-up of the compression parallel-to-grain test showing wood being deformed by the instrument.



### 4.3 Product Analysis

The product was visually tested for surface color, warping and fracturing. At high temperature, the presence of dark coloration indicated that the wood may be burned or oxidized. If the wood cupped or bent slightly, it was deemed unacceptable. In addition, the presence of fractures along the wood surface indicated that the rate of drying may be too fast and the drying condition must be adjusted. Figure 4.5 illustrates examples of warped and fractured pieces of wood.



Figure 4.5: Examples of unacceptable pieces of dried wood showing (a) warp and (b) fracture.

### 4.4 Data Analysis

Experimental data were averaged and analyzed using Microsoft® Excel 2002. All experiments were performed at least in duplicate.

## CHAPTER V

### RESULTS AND DISCUSSION

#### 5.1 Experimental Results

Due to the large number of experiments that were conducted, not all results will be discussed here. Detailed results of all the experiments along with discussions of the problems encountered and solutions implemented are presented in Appendix B.

##### 5.1.1 Drying Rates

Figure 5.1 illustrates the drying curves for superheated steam drying at 110°C and hot air drying at 80°C, and Figure 5.2 shows the drying curves at various combinations of superheated steam and hot air. The y-axis represents the moisture content in dry basis (d.b.) and the x-axis is the drying time in hours (hr). The curves depict the general drying curve which consists of 3 distinct periods: (1) the initial heating period, (2) the constant drying period, and (3) the falling rate period. The initial period, characterized by a rapid increase in temperature of the wood from initial temperature to the boiling point of water, is not clearly shown below since the time frame is small compared to the total drying time. The rapid increase in temperature is shown in Figures 5.3 and 5.4 in Section 5.1.2.

From Figure 5.1, the drying rates of both the superheated steam and the hot air were much faster than the conventional methods which take several days for the moisture content of the wood to reach 0.25 d.b. This was due to the impingement technique which caused rapid heat transfer from the superheated steam to the surface of the wood due to the directional flow of the steam from the perforated pipes. As a result of the higher rate of heat transfer, there was also an increase in the rate of moisture loss from the wood.

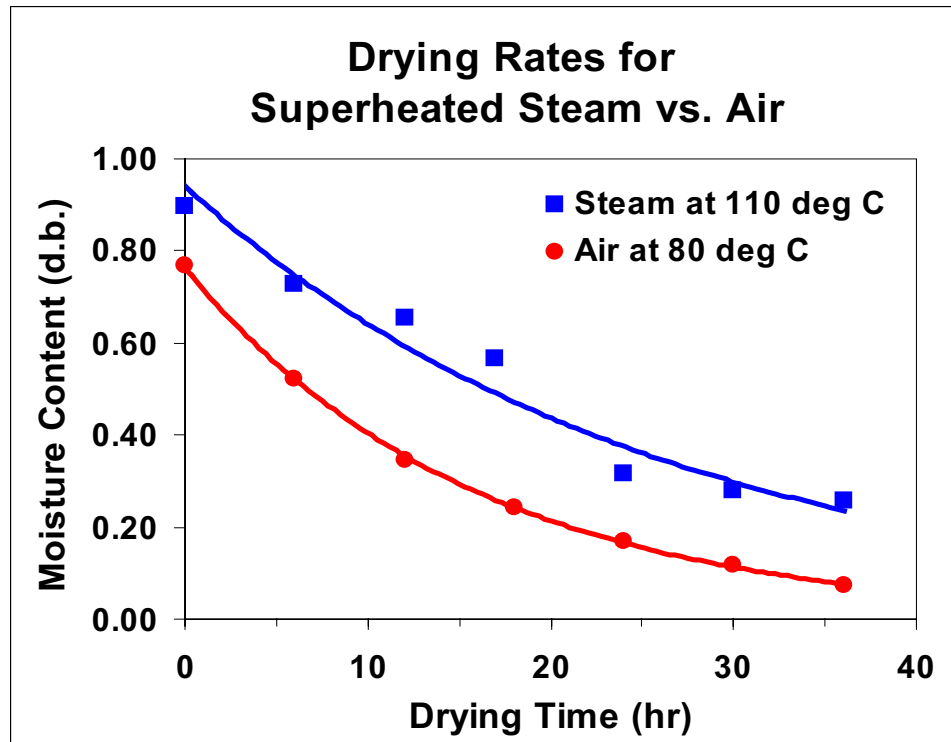


Figure 5.1: Drying rates of superheated steam at 110°C vs. hot air at 80°C.

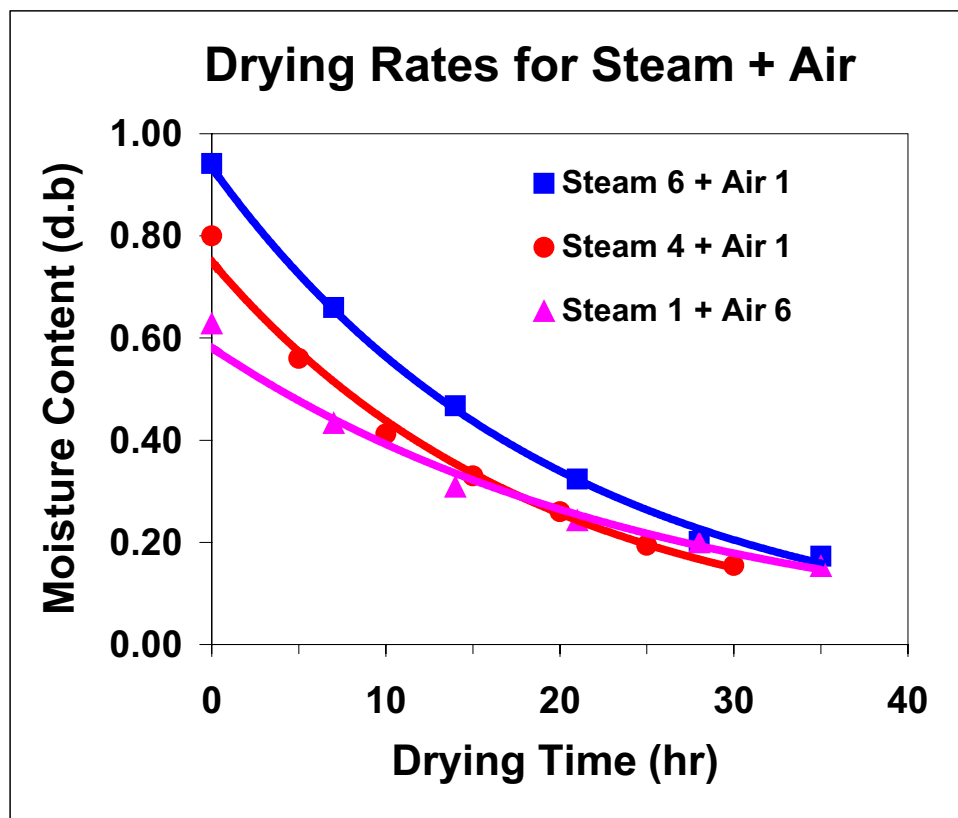


Figure 5.2: Drying rates at various combinations of superheated steam and air.

Moreover, the constant rate of drying for hot air was faster than that of the superheated steam case due to lower humidity that developed inside the chamber. After 25 hours of drying, the rate of water loss for the superheated steam case was quite low due to the high

amount of water vapor that existed inside the chamber. Since the rate of water vapor leaving the vent and the rate of vapor condensation were less than that of the entering steam, the humidity inside the chamber remained high causing the removal of the bound water to be very difficult. Hence, it was essential that the humidity of the chamber be reduced in order to decrease the equilibrium moisture content (EMC) of the rubberwood.

Figure 5.2 demonstrates that the moisture content of the rubberwood can be reduced to less than 0.20 d.b. using a combination of steam and hot air. Even though the case for 6:1 steam to air ratio scenario began at a higher initial moisture content, the slopes of the drying curve was very similar to that of the 4:1 steam to air scenario. A discussion of why the former case was preferred over the 4:1 and 1:6 cases will be given in a later section.

### 5.1.2 Temperature profile

Figure 5.3 illustrate the cross section of the board and the locations of the thermocouples. Figures 5.4 and 5.5 show the temperature profiles ( $^{\circ}\text{C}$ ) at the center and at the surface of the wood as a function of drying time (hr). The condition analyzed was for 4:1 steam to air ratio and a superheated steam temperature of  $110^{\circ}\text{C}$ . As mentioned previously, the temperature at each point increase steadily until the boiling point of water was reached (slightly lower than  $100^{\circ}\text{C}$  due to dissolved solutes in the water). For example, it took about 1.4 hours for the temperature at the surface to reach  $98^{\circ}\text{C}$ , while it took 2 hours for the temperature at the center to reach the same value. Additionally, it took 1.6 hours for the surface temperature to reach  $99^{\circ}\text{C}$ , while it required over 10 hours for the center temperature to reach the same mark. After 10 hours of drying, the moisture content dry basis had reduced from 0.80 to 0.41 d.b. This average value was still above the fiber saturation point denoting that there was still continuous removal of free water. Table 5.1 shows the average moisture content (d.b.) as a function of drying time for the 4:1 steam to air ratio.

Table 5.1 Moisture content of 4:1 steam to air ratio using superheated steam at  $110^{\circ}\text{C}$ .

| <b>Drying Time<br/>(hours)</b> | <b>Moisture Content<br/>(d.b.)</b> |
|--------------------------------|------------------------------------|
| 0                              | 0.80                               |
| 5                              | 0.56                               |
| 10                             | 0.41                               |
| 15                             | 0.33                               |
| 20                             | 0.26                               |
| 25                             | 0.19                               |
| 30                             | 0.15                               |

Furthermore, Figure 5.5 illustrates that even after the 30 hours of drying, the temperature at the center and surface of the wood remained near  $100^{\circ}\text{C}$  indicating the presence of water vapors in the center and at the surface of the wood. At this point, the moisture content has been reduced to 0.15 d.b. Hence, the water remaining inside the wood was mostly water bounded along the cell walls. In addition, the figure also demonstrates that it took a relatively short amount of time for the wood to reach nearly a uniform temperature throughout the wood. This is assuming that the seal at the side surface where the thermocouple wire was inserted effectively prevented the steam from entering the bored hole (see Figure 5.3).

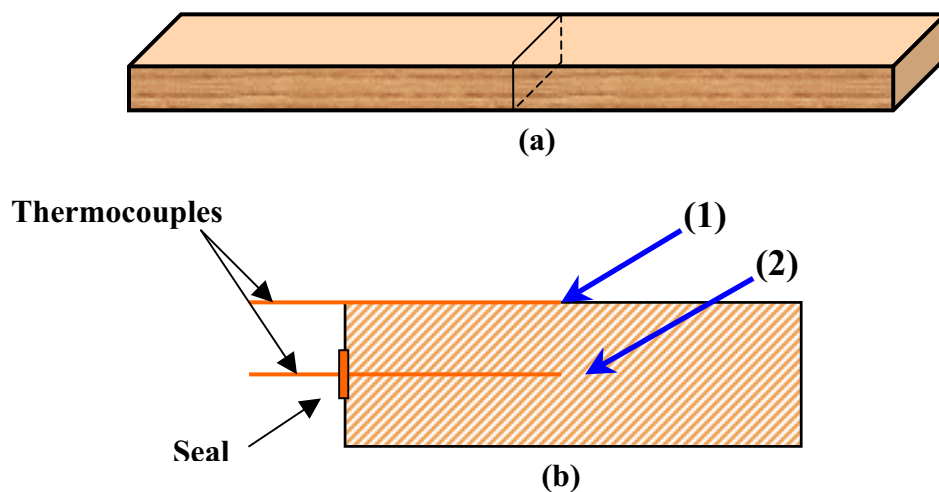


Figure 5.3: (a) View of board, showing the cross section where the thermocouples were inserted. (b) Cross-section view of the board showing the locations of the thermocouples (1) at the surface and (2) at the center.

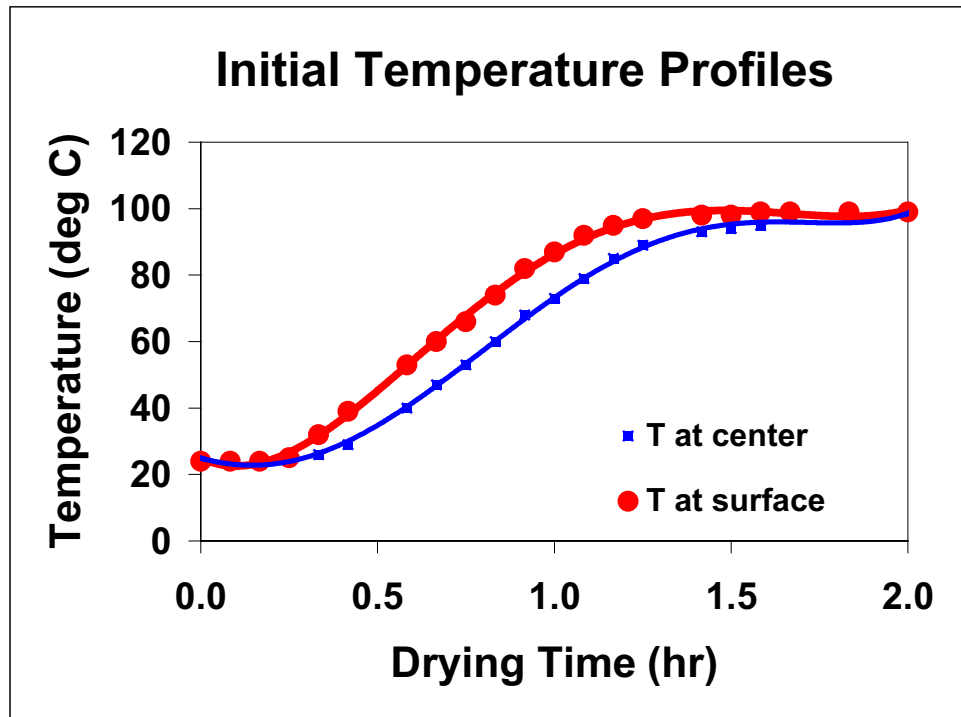


Figure 5.4: Initial temperature profiles at the center and at the surface of the wood. Superheated steam at 110°C and 4:1 steam to air ratio.

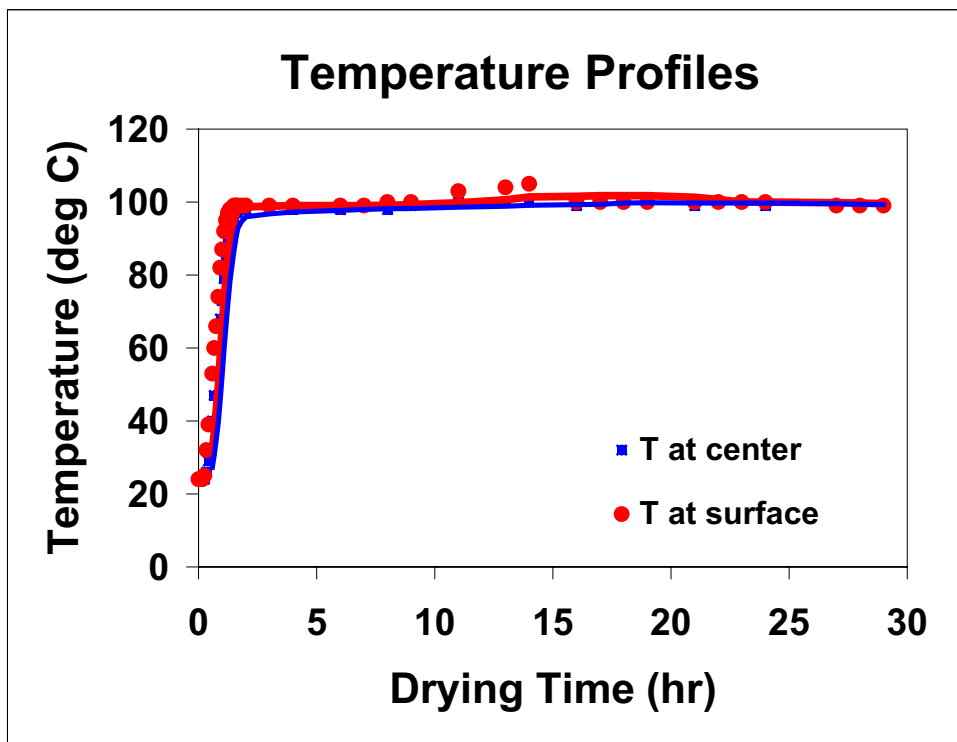


Figure 5.5: The overall temperature profile after 30 hr of drying. Superheated steam at 110°C and 4:1 steam to air ratio.

## 5.2 Physical Analysis

Table 5.2 shows the results from the prong tests for cases in which the acceptable moisture content was reached (approximately 0.15 d.b.). Even though Cases 3, 4, and 5 (steam 4: air 1, steam 1: air 6, and air only) all reached the acceptable moisture content range, their rates of moisture loss may have been too rapid, causing excessive stress buildup which led to their failing the prong test. Figure 5.6 depicts the results of the prong test for drying with hot air only and using a 6:1 ratio of superheated steam to hot air. The figure shows that there was a significant amount bending of the prong in the hot air only case, while the latter case did show significant bending of the prong. Hence, this condition was considered for the optimization study and for the mechanical properties testing.

Table 5.2 Results of prong test.

| Case | Condition      | EMC less than 0.20 d.b. | Passed Prong Test |
|------|----------------|-------------------------|-------------------|
| 1    | Steam only     | No                      | -                 |
| 2    | Steam 6: Air 1 | Yes                     | Yes               |
| 3    | Steam 4: Air 1 | Yes                     | No                |
| 4    | Steam 1: Air 6 | Yes                     | No                |
| 5    | Air only       | Yes                     | No                |

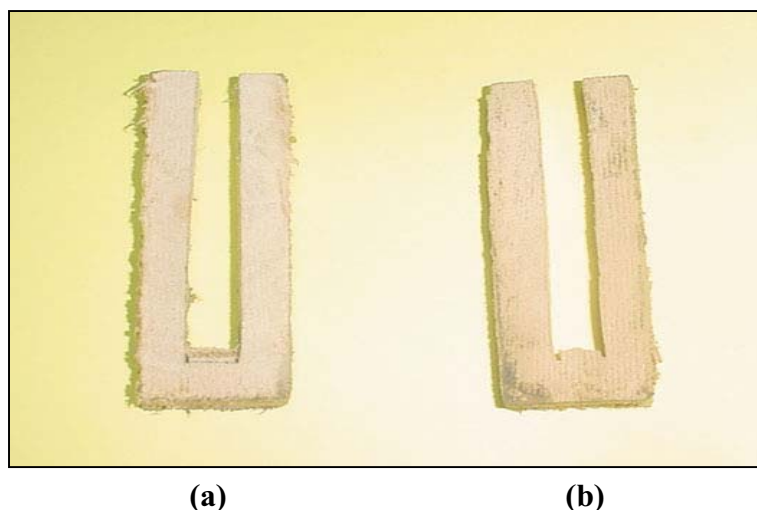


Figure 5.6: (a) Hot air dried wood showing slight bending of the prong. (b) Superheated steam 6: air 1 case showing the lack of stress buildup.

Since the results from the prong test indicated that a combination of superheated steam and hot air was able to reduce the moisture content of the wood without resulting in excessive stress buildup, optimization study was conducted. Finally, the schedule developed during

the optimum study was used for the mechanical properties testing. This included testing for shear parallel to grain and compression parallel to grain.

Furthermore, the coloration of the dried samples using superheated steam at 110°C did not cause any burnt spots or discoloration of the wood. As can be seen in Figure 5.6, the color of the sample was not greatly affected by the high temperature. This may be due to the influence of the superheated steam heat transferring medium which prevented oxidizing of the wood surface during the drying process.

### 5.3 Optimization Study

Several drying schedules were studied to examine the influence of various combinations of superheated steam and hot air. These investigations focused on lower initial steam temperature in order to reduce the initial stress buildup that led to warping and cracking of the lumber boards. Table 5.3 details the most effective schedule studied within the scope of this research and Table 5.4 gives the moisture content as a function of drying time for this particular case. In addition, the drying curve for the optimized case compared to the 6:1 steam to air ratio is shown in Figure 5.7. From the figure, it can be seen that the rates are very similar. However, a close look shows that after 7 hours of drying, the moisture content (d.b.) of the optimized condition was 0.76 compared to 0.66 for the 6:1 case. This slower initial rate helped to maintain an acceptable stress gradient within the wood, which consequently resulted in reduced stress development. See Appendix C.5 for images of the wood dried at this condition.

Table 5.3 Optimized drying schedule.

| Period                     | Description                                                                                |
|----------------------------|--------------------------------------------------------------------------------------------|
| 0 – 7 <sup>th</sup> hour   | Start of by drying with steam at 100°C for 4 hours followed by steam at 105°C for 3 hours. |
| 8 – 14 <sup>th</sup> hour  | Dry with superheated steam at 105°C for 6 hours followed by hot air at 90°C for 1 hour.    |
| 15 – 21 <sup>st</sup> hour | Dry with superheated steam at 110°C for 6 hours followed by hot air at 90°C for 1 hour.    |
| 22 – 26 <sup>th</sup> hour | Dry with superheated steam at 110°C for 4 hours followed by hot air at 90°C for 1 hour.    |
| 27 – 31 <sup>st</sup> hour | Dry with superheated steam at 110°C for 4 hours followed by hot air at 90°C for 1 hour.    |
| 32 – 35 <sup>th</sup> hour | Dry with superheated steam at 110C for 1 hour followed by hot air at 80°C for 3 hours.     |
| 36 – 41 <sup>st</sup> hour | Dry with superheated steam at 110C for 1 hour followed by hot air at 80°C for 5 hours.     |

Table 5.4 Moisture content of the optimized drying schedule as a function of drying time.

| <b>Drying Time<br/>(hours)</b> | <b>Moisture Content<br/>(d.b.)</b> |
|--------------------------------|------------------------------------|
| 0                              | 0.92                               |
| 7                              | 0.76                               |
| 14                             | 0.45                               |
| 21                             | 0.30                               |
| 26                             | 0.24                               |
| 31                             | 0.23                               |
| 36                             | 0.20                               |
| 30                             | 0.16                               |

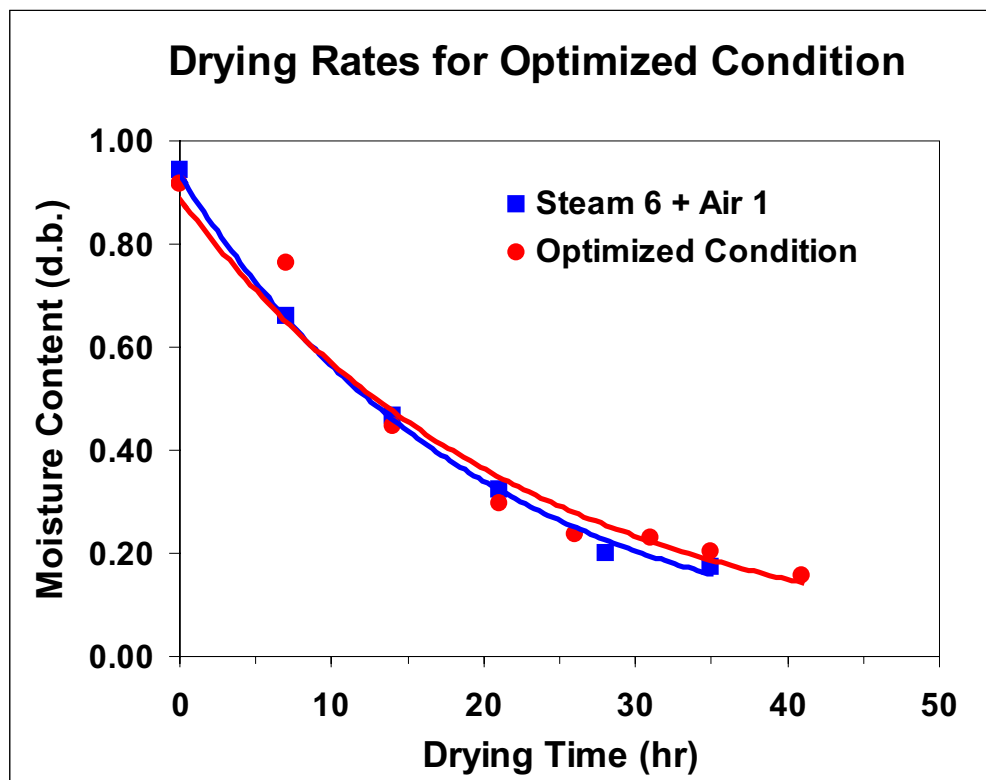


Figure 5.7: Drying of the optimized condition compared to the 6:1 steam to air ratio case.

In addition, even though the optimized case required a longer period of drying compared to the 6:1 scenario, it is still practical since it takes less than 2 days for the moisture content to reach 0.15 d.b. Therefore, the optimized case was selected for the mechanical properties measurements.

## 5.4 Mechanical Properties Tests

For mechanical properties tests, 3 pieces of lumber Grade A and B (depending on the availability) were clamped and dried together as shown in Figure 5.8. Twenty random samples were prepared for each of the mechanical tests according to ASTM D1990-91 where the moisture content of each sample was adjusted to about 12% dry basis prior to the testing. The mechanical properties determined included the shear parallel to grain, the compression parallel and perpendicular to grain, the static bending tests (modulus of elasticity and the modulus of rupture), and the hardness. Tables 5.5 and 5.6 illustrate the specific gravity (SG) and the moisture content dry basis (MC) of samples dried using the optimized condition and those taken from Rutthapoom Parawood, respectively. Values are similar to those published in Kyokong and Dounget (2000).

Finally, the results of the mechanical properties are listed in Table 5.7 and the deviations between the experimental results and the reference vales are shown in Table 5.8. From the tables, both the shear parallel to grain and the compression strength parallel to grain for the optimized drying condition were higher than the literature values. However, the strength perpendicular to grain and the modulus of elasticity (MOE) values were significantly lower than those from the literature. Nonetheless, the modulus of rupture (MOR) was substantially higher than that of the reference indicating that the wood dried using superheated steam can withstand a high breaking force. Moreover, a high MOE value does not necessary mean the wood is stronger since it indicates a higher fracturability and brittleness of the wood. On the hand, the comparable values of the hardness indicate that the wood is sufficiently hard for the various furnishing applications.

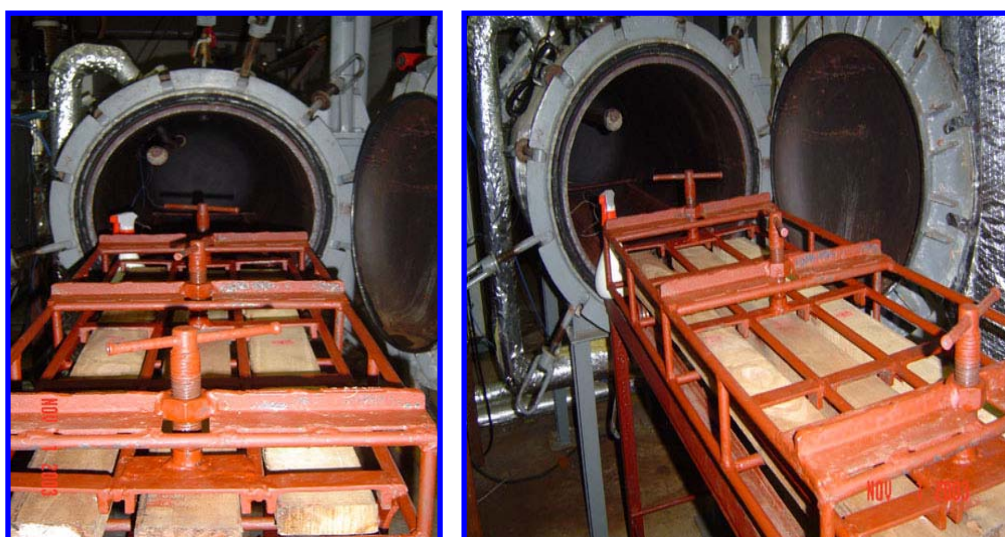


Figure 5.8: Three pieces of boards clamped and dried using the optimum drying schedule.

Table 5.5 Specific gravity of wood samples used for mechanical properties testing.

| Condition                      | Properties               | Specific Gravity |         |             |         |
|--------------------------------|--------------------------|------------------|---------|-------------|---------|
|                                |                          | Minimum          | Maximum | Mean        | COV (%) |
| <b>1. Optimized Condition</b>  | Shear Parallel to Grain  | 0.50             | 0.58    | <b>0.55</b> | 4.07    |
|                                | Compression              |                  |         |             |         |
|                                | • Parallel to Grain      | 0.52             | 0.61    | <b>0.56</b> | 3.83    |
|                                | • Perpendicular to Grain | 0.54             | 0.69    | <b>0.65</b> | 7.45    |
|                                | Hardness                 | 0.54             | 0.71    | <b>0.60</b> | 7.90    |
|                                | Static Bending           | 0.53             | 0.68    | <b>0.64</b> | 7.46    |
| <b>2. Conventional Drying*</b> | Shear Parallel to Grain  | 0.66             | 0.73    | <b>0.70</b> | 3.50    |
|                                | Compression              |                  |         |             |         |
|                                | • Parallel to Grain      | 0.65             | 0.73    | <b>0.68</b> | 2.85    |
|                                | • Perpendicular to Grain | 0.66             | 0.75    | <b>0.69</b> | 3.05    |
|                                | Hardness                 | 0.65             | 0.73    | <b>0.68</b> | 2.72    |
|                                | Static Bending           | 0.64             | 0.74    | <b>0.69</b> | 3.83    |

\*From Rutthapoom Parawood

Table 5.6 Moisture content of wood samples used for mechanical properties testing.

| Condition                      | Properties               | Moisture Content (% d.b.) |         |              |         |
|--------------------------------|--------------------------|---------------------------|---------|--------------|---------|
|                                |                          | Minimum                   | Maximum | Mean         | COV (%) |
| <b>1. Optimized Condition</b>  | Shear Parallel to Grain  | 12.70                     | 13.90   | <b>13.32</b> | 2.88    |
|                                | Compression              |                           |         |              |         |
|                                | • Parallel to Grain      | 12.76                     | 13.51   | <b>13.17</b> | 1.40    |
|                                | • Perpendicular to Grain | 12.98                     | 13.56   | <b>13.28</b> | 1.26    |
|                                | Hardness                 | 11.74                     | 12.20   | <b>12.02</b> | 0.90    |
|                                | Static Bending           | 13.25                     | 13.97   | <b>13.60</b> | 1.68    |
| <b>2. Conventional Drying*</b> | Shear Parallel to Grain  | 8.25                      | 10.16   | <b>9.38</b>  | 5.03    |
|                                | Compression              |                           |         |              |         |
|                                | • Parallel to Grain      | 9.37                      | 10.0    | <b>9.69</b>  | 1.68    |
|                                | • Perpendicular to Grain | 9.06                      | 9.85    | <b>9.38</b>  | 2.32    |
|                                | Hardness                 | 8.98                      | 9.89    | <b>9.44</b>  | 2.40    |
|                                | Static Bending           | 8.85                      | 9.49    | <b>9.15</b>  | 1.67    |

\*From Rutthapoom Parawood

Table 5.7 Mechanical properties of dried rubberwood.

| <b>Properties</b>                        | <b>Superheated<br/>Steam Drying</b> | <b>Conventional<br/>Drying*</b> | <b>Reference**</b> | <b>p</b> |
|------------------------------------------|-------------------------------------|---------------------------------|--------------------|----------|
| <b>Shear Parallel to Grain<br/>(MPa)</b> | 13.66 ± 1.44                        | 15.35 ± 1.23                    | 11.0               | 0.000    |
| <b>Compression (MPa)</b>                 |                                     |                                 |                    |          |
| • <b>Parallel to Grain</b>               | 37.10 ± 2.14                        | 52.66 ± 4.21                    | 32.0               | 0.000    |
| • <b>Perpendicular to Grain</b>          | 1.93 ± 0.31                         | 2.06 ± 0.18                     | 5.0                | 0.040    |
| <b>Static Bending (MPa)</b>              |                                     |                                 |                    |          |
| • <b>Modulus of Rupture<br/>(MOR)</b>    | 91.40 ± 7.85                        | 107.06 ± 11.42                  | 66.0               | 0.000    |
| • <b>Modulus of Elasticity<br/>(MOE)</b> | 7388 ± 1138                         | 9721 ± 1606                     | 9240.0             | 0.000    |
| <b>Hardness (N)</b>                      | 4259 ± 570                          | 4890 ± 482                      | 4350.0             | 0.001    |

Sources: \*Rutthapoom Parawood

\*\*Killmann. W. and Hong. L.T. (2002)

Table 5.8 Comparison with literature values.

| <b>Properties</b>                        | <b>Superheated<br/>Steam Drying</b> | <b>Reference**</b> | <b>Deviation</b> |
|------------------------------------------|-------------------------------------|--------------------|------------------|
| <b>Shear Parallel to Grain<br/>(MPa)</b> | <b>13.66</b>                        | <b>11.0</b>        | <b>22.4%</b>     |
| <b>Compression (MPa)</b>                 |                                     |                    |                  |
| • <b>Parallel to Grain</b>               | <b>37.10</b>                        | <b>32.0</b>        | <b>15.9%</b>     |
| • <b>Perpendicular to Grain</b>          | <b>1.93</b>                         | <b>5.0</b>         | <b>-61.4%</b>    |
| <b>Static Bending (MPa)</b>              |                                     |                    |                  |
| • <b>Modulus of Rupture<br/>(MOR)</b>    | <b>91.4</b>                         | <b>66.0</b>        | <b>38.5%</b>     |
| • <b>Modulus of Elasticity<br/>(MOE)</b> | <b>7388.0</b>                       | <b>9240.0</b>      | <b>-20.0%</b>    |
| <b>Hardness (N)</b>                      | <b>4259.0</b>                       | <b>4350.0</b>      | <b>-2.1%</b>     |

Sources: \*Rutthapoom Parawood

\*\*Killmann. W. and Hong. L.T. (2002)

Figures 5.9 and 5.10 compare the mean values of the optimized drying condition, the conventional drying condition, and those taken from literature. Statistical analysis of the data using the paired comparison design shows significant difference ( $p < 0.05$ ) between the optimized drying condition and the conventional drying conditions. Values of the shear and compression parallel to grain, the compression perpendicular to grain, the MOR, the MOE, and the hardness were all significantly lower at 95% confidence level. This agrees with results from Bekhta and Niemz (2003) who showed that high temperature drying has a significant influence on the mechanical properties of Spruce wood. However, Thiam, Milota and Leichti (2002) found no significant effect of temperature on the mean MOR, MOE and shear strengths of Western Hemlock lumber after drying under high temperature.

Moreover, moisture content is an important factor influencing the mechanical properties of the wood. Since specimens from the optimized drying and the conventional drying had varying moisture content, 13% to 9%, respectively, the mechanical properties of the latter are higher as expected. Although most properties will continue to increase with lower moisture content, some properties reach a maximum value and then decrease with further drying (USDA, 1999; Kretschmann and Green, 1996; Matan and Kyokong, 2002).

Finally, even though the values of the optimized condition are lower than the conventional drying scenario, the values still compare relatively well with the literature values. Deviations in the values in all cases may have resulted from the non-uniformity of the raw materials and the specimens selected for measurements.

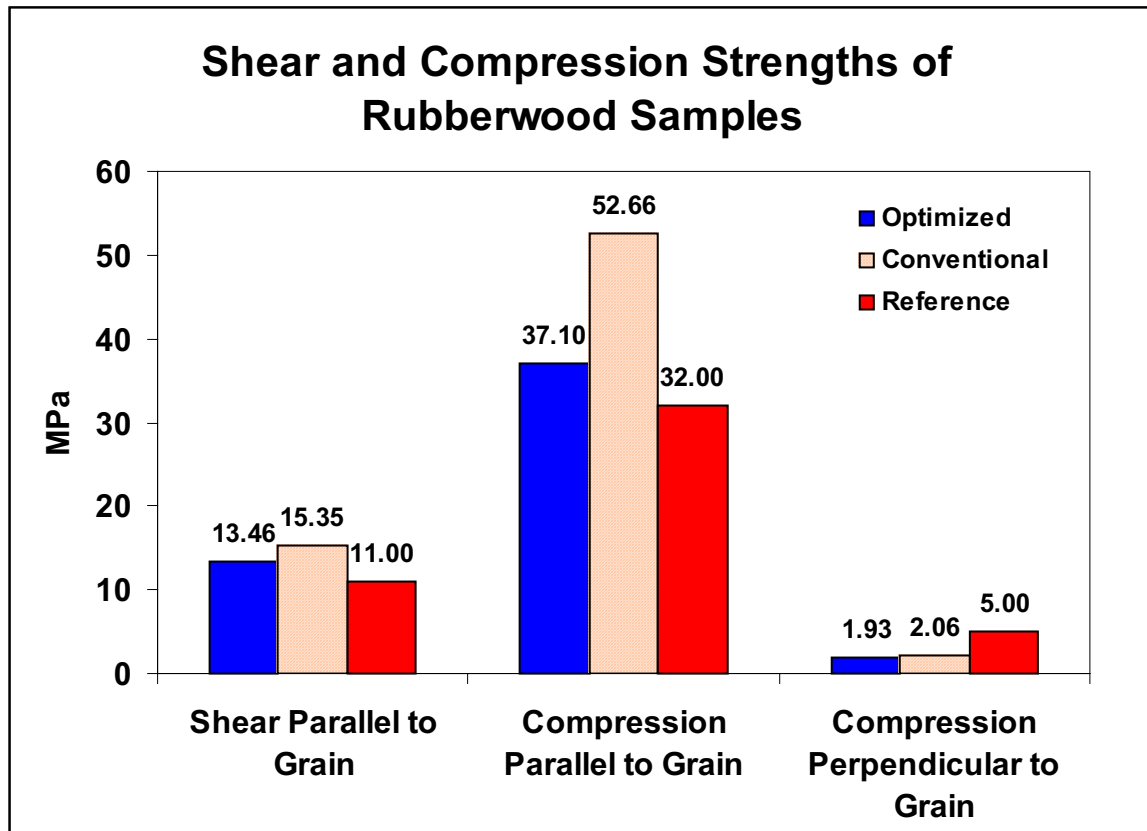


Figure 5.9: Shear and compression strengths of wood samples tested.

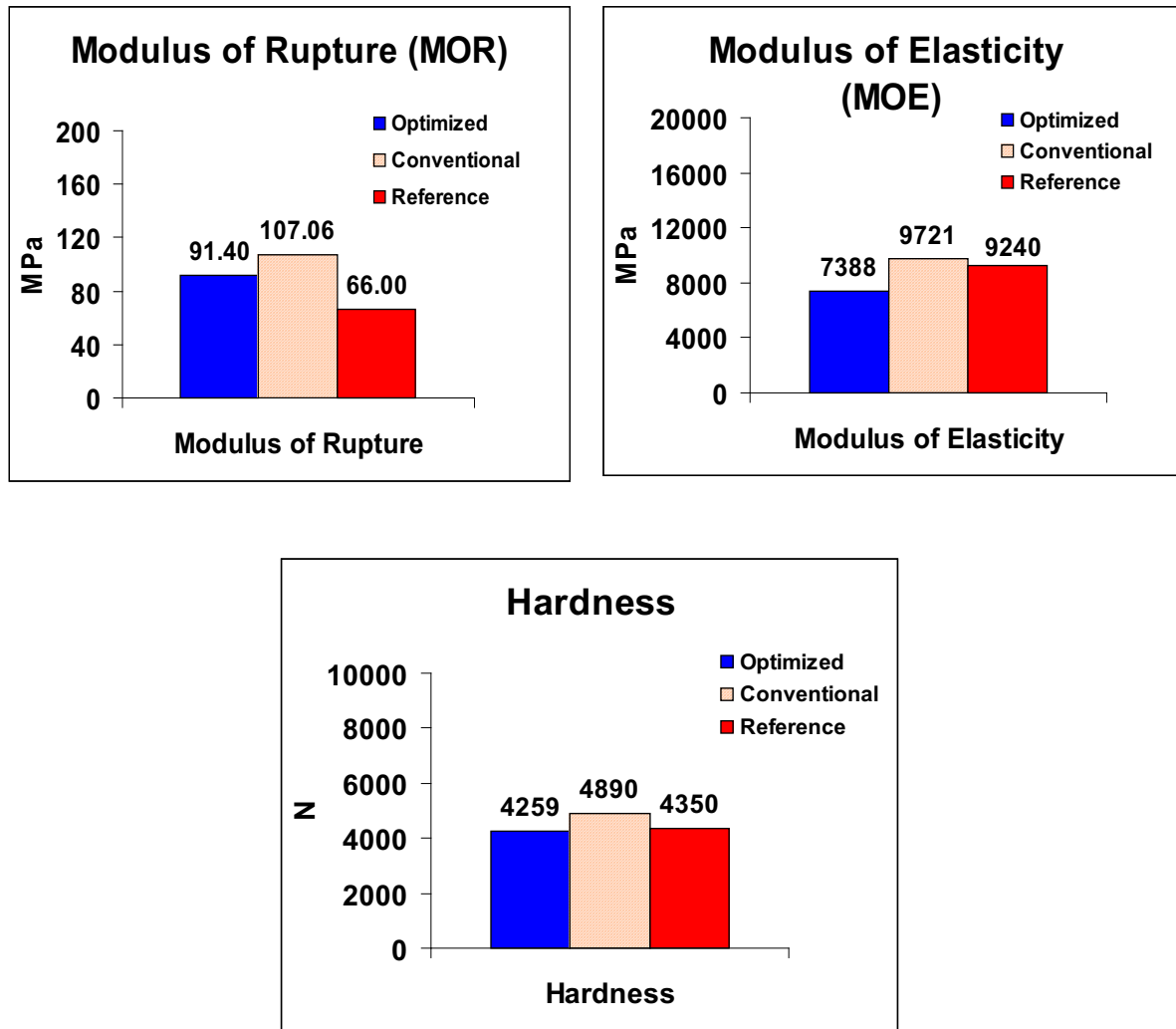


Figure 5.10: Static bending and hardness results of wood samples tested: (a) Modulus of Rupture (MOR), (b) Modulus of Elasticity (MOE), and (c) Hardness.

## 5.5 Energy Savings Potential

From preliminary studies, superheated steam drying presents a significant energy savings in terms of drying time. In traditional wood drying operations in Thailand, boilers are used to generate steam which then is fed into heating coils for the heating of hot air blown in by compressors. The fuel source for the boiler is wood chips and wood dusts that are inexhaustible byproducts of the wood cutting process. Therefore, the generation of superheated steam using heating coils of high pressure, high temperature steam or even electrical coils can reduce drying operations by as much as 75%. Figure 5.11 presents the potential energy savings offered by this technique in terms of drying time.

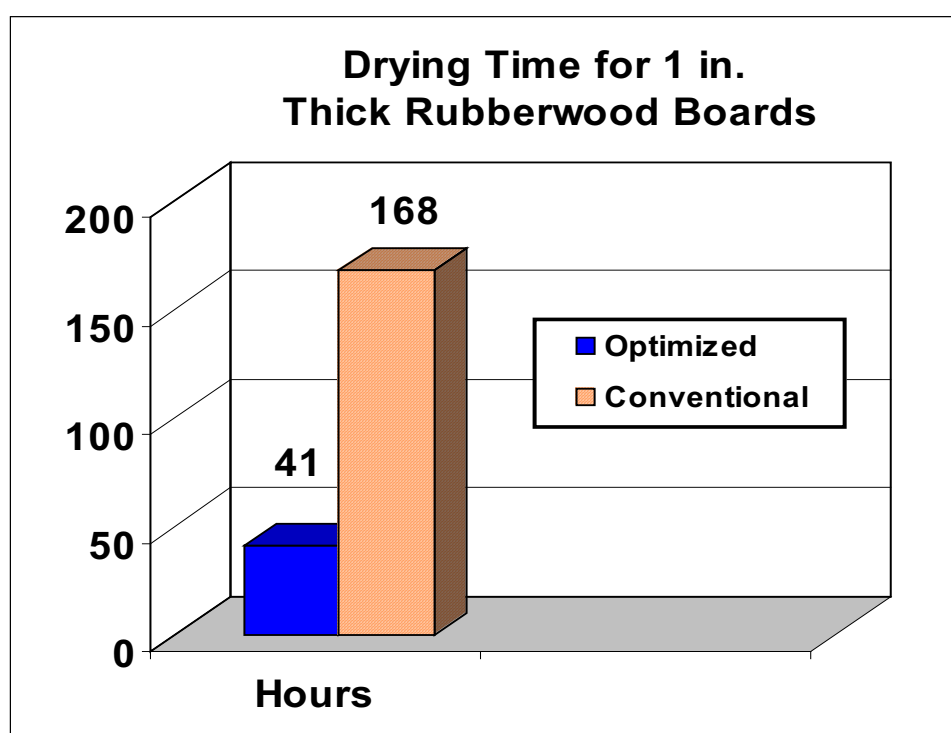


Figure 5.11: Drying time comparison between optimized condition and the conventional drying for 1 in. thick rubberwood board.

## CHAPTER VI

### CONCLUSIONS AND RECOMMENDATIONS

#### 6.1 Conclusions

A lab-scale superheated steam dryer was constructed to study effectiveness of superheated steam the drying of rubberwood. Experiments indicated that a significantly shorter drying time can be obtained by using a combination of superheated steam and hot air. In addition, the mechanical property of the rubberwood boards can also be maintained. The following conclusions are then obtained from this study.

1. Superheated steam drying alone cannot decrease the moisture content of the wood below the Fiber Saturation Point due to the high humidity inside the drying chamber.
2. Combinations of superheated steam and hot air drying can reduce the moisture content of the product to below 0.20 moisture content dry basis; however, not all conditions will pass the prong test due to excessive stress buildup.
3. The color of the rubberwood was not significantly affected by the drying temperature, especially for the optimum drying condition.
4. The clamping devices significantly decreased the warping of the wood during the drying process.
5. The optimized drying condition should maintain a low steam temperature during the initial period of drying followed by air intermittently.
6. The superheated steam can be used in the latter stages of drying to increase the rate of moisture loss without increasing the stress inside the wood. This is due to the slow initial drying period.
7. The optimized drying condition can maintain the mechanical properties of the wood, specifically the shear parallel to grain, the compression strength parallel to grain, and the hardness of the product.
8. The optimized drying condition can reduce the overall drying time for 1 in. thick rubberwood boards from 7 days to less than 2 days on a lab scale basis.
9. The operational cost of the drying process will decrease due to the reducing drying time and since the superheated steam will only be used at intermittent intervals, the cost of superheating the steam will be minimal compared to the longer drying time of the conventional process.

## 6.2 Recommendations for Future Work

The study presented in this work is just the beginning of many fascinating studies lying ahead. For example, numerous combinations of drying conditions can be used in order to minimize the drying time even more. The possibility of using superheated steam at lower temperature for the drying of rubberwood is also intriguing and represents another viable option. Furthermore, more research must be conducted in this area and a larger, more practical unit must be developed for industrial usage. Here are some suggestions for future work.

1. The new pilot scale unit must be able to handle large volume of rubberwood boards.
2. The steam should be constantly removed, filtered and recycled to save energy and maintain a low humidity drying condition. This is essential during the bound water removal period.
3. A relative humidity (RH) meter should be installed to actively monitor the moisture content inside of the drying chamber.
4. The drying chamber should be located within a short distance of the boiler to minimize heat loss.
5. Maintenance to be done regularly to prevent corrosion of the pipes and rusting of the drying chamber. Steam traps must also be checked frequently, because corrosive chemicals used to treat the lumber may seep out and eat away the steam trap. The steam trap can also become clogged which could lead to flooding inside the chamber.

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## **APPENDIX A**

### **TESTS OF MECHANICAL PROPERTIES OF WOOD**

#### **A.1 Control of Moisture and Temperature**

- **Control of Moisture Content**

The seasoned sticks, whether kiln-dried or air-dried, preferably should be stored in a room having controlled temperature and humidity ( $20\pm 2^{\circ}\text{C}$  and  $65\pm 3\%$  relative humidity) before test to reduce the moisture gradient within the material, and to bring the material into equilibrium, which will be approximately 12% moisture content for most specimens.

Sticks test in the air-dry condition shall be brought practically to constant weight before test. Should any changes in moisture content occur during final preparation specimens, of specimens shall be reconditioned before test to constant weight under conditions  $20\pm 2^{\circ}\text{C}$  and  $65\pm 3\%$  relative humidity. Tests shall be carried out in such manner that large change in moisture content will not occur. To prevent such changes, it is desirable that the testing room and rooms for preparation of test specimens have some means of humidity control.

- **Control of Temperature**

Independent of the effect of moisture content on the strength of the test specimens is the significant effect of temperature itself on the mechanical properties. The specimens when tested shall be at a temperature of  $20\pm 2^{\circ}\text{C}$ .

## **A.2 Moisture Determination**

- **Selection**

The sample for moisture determination of each test specimen shall be selected as herein before described for each test.

- **Weighing**

Immediately after obtaining the moisture sample, all loose splinters shall be removed and the sample shall be weighed.

- **Drying**

The moisture samples shall be open piled in an oven and dried at a temperature of  $103\pm 2^{\circ}\text{C}$  until approximately constant weight is attained, after which the oven-dry weight shall be determined.

- **Moisture Content**

The loss in weight, expressed in percentage of the oven-dry weight as above determined, shall be considered the moisture content of the specimen.

### A.3 Specific Gravity

- **Procedure**

Obtain both specific gravity and moisture content determinations on the same specimen. Weigh the specimen when green and determine the volume. Dry in an oven and dry at  $103\pm 2^{\circ}\text{C}$  until approximately constant weight is reached. After oven drying, weigh the specimen.

- **Calculation of Results**

The results are given in terms of Specific Gravity, SG, and can be expressed as:

$$SG = \frac{W_o}{V_t}$$

Where  $W_o$  is the weight after dried and  $V_t$  is the volume during testing.

## A.4 Compression Parallel to Grain

- **Size of Specimen**

The compression-parallel-to-grain tests shall be made on nominal 20 by 20 by 60 mm specimens. The actual cross-section dimensions and the length shall be measured. Measurements of test specimens shall be measured by caliper (to 2 decimal places).

- **Loading Method**

The specimen shall be placed in compression parallel to grain. Special care shall be used in preparing the compression-parallel to grain test specimens to ensure that the end grain surface will be parallel to each other and at right angles to the longitudinal. If deemed necessary, at least on platen of the testing machine shall be equipped with a spherical bearing to obtain uniform distribution of load over the ends of the specimen. (See Figure A.1)

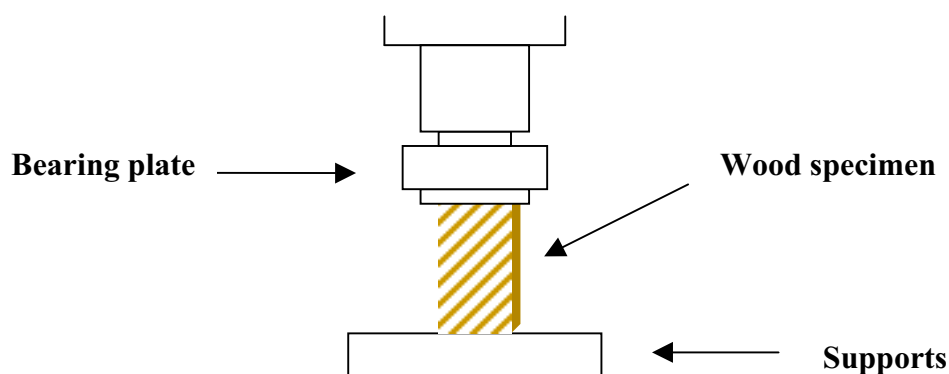


Figure A.1: Compression-parallel-to-grain test.

- **Compression Failures**

Compression failure shall be classified according to the appearance of the fractured surface (shown in Figure A-2):

- 1) *Crushing*: This term shall be used when the plane of rupture is approximately horizontal.
- 2) *Shearing*: This term shall be used when the plane rupture makes an angle of more than 45 deg with the top of the specimen.
- 3) *Wedge Split*: The direction of the split, that is whether radial or tangential, shall be noted.
- 4) *Splitting*: This type of failure usually occurs in specimens having internal defects prior to test culling the specimen.

5) *Compression and Shearing Parallel to Grain*: This failure usually occurs in cross grained pieces and shall be the basis for culling the specimen.

6) *Brooming or End-Rolling*: This type of failure is usually associated with either an excess moisture content at the ends of the specimen, improper cutting of the specimen, or both. This is not an acceptable type of failure and usually is associated with a reduced load. Consideration should be given to remedial conditions when this type of failure is observed.

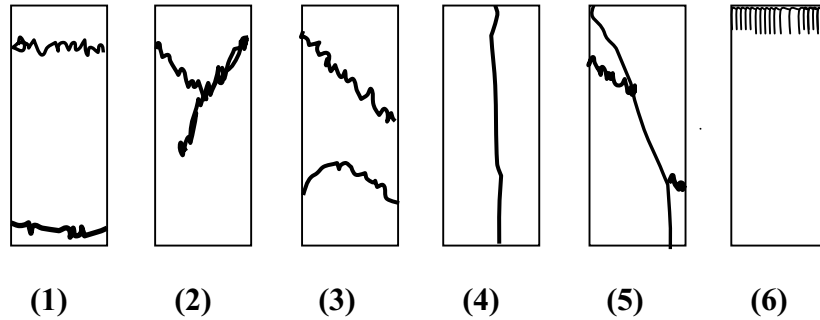


Figure A.2: types of failures in compression.

- **Specific Gravity and Moisture Content**

See sections A.2 and A.3.

- **Calculation of Results**

The results are given in term of Ultimate stress in compression parallel to grain,  $\sigma_c$  and can be expressed as:

$$\sigma_c (Mpa) = \frac{P_{max}}{(a) \times (b)}$$

Where,  $P_{max}$  = Maximum load (N or kg)

$(a) \times (b)$  = Surface area ( $mm^2$  or  $cm^2$ ).

## A. 5 Compression Perpendicular to Grain

- **Size of Specimen**

The compression-parallel-to-grain tests shall be made on nominal 20 x 20 x 60 mm specimens. The actual cross-section dimensions and the length shall be measured. Special care shall be used in preparing the compression-parallel to grain test specimens to ensure that the end grain surface will be parallel to each other and at right angles to the longitudinal. Measurements of test specimens shall be measured by caliper (to 2 decimal places).

- **Loading Method**

The load shall be applied through a metal bearing plate 20 mm in width, placed across the upper surface of the specimen at equal distances from the ends and at right angles to the length (Figure A.3).

The specimens shall be placed so that the load will be applied through the bearing plate to a radial (quarter-sawed) surface.

The load shall be applied continuously throughout the test at a rate of motion of the movable crosshead of 0.305 mm/min.

Load-compression curve shall be taken for all specimens up to 2.5 mm compression, after which the test shall be discontinued.

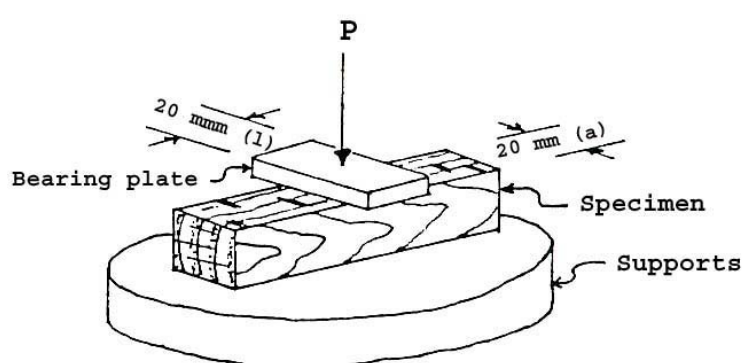


Figure A.3: Compression-parallel-to-grain test.

- **Specific Gravity and Moisture Content**

See sections A.2 and A.3.

- **Calculation of Results**

Load (y-axis) is plotted against deformation (x-axis) (Figure A.4) and  $\sigma_{P.L.}$  can be expressed:

$$\sigma_{P.L.} = \frac{P_{P.L.}}{A}$$

Where,  $\sigma_{P.L.}$  = Fiber stress at proportional limit (MPa)

= Conventional strength in compression perpendicular to grain

$P_{P.L.}$  = Load at proportional limit (N or kg)

$A$  = Width of specimen (a)  $\times$  Width of metal bearing plate (l)

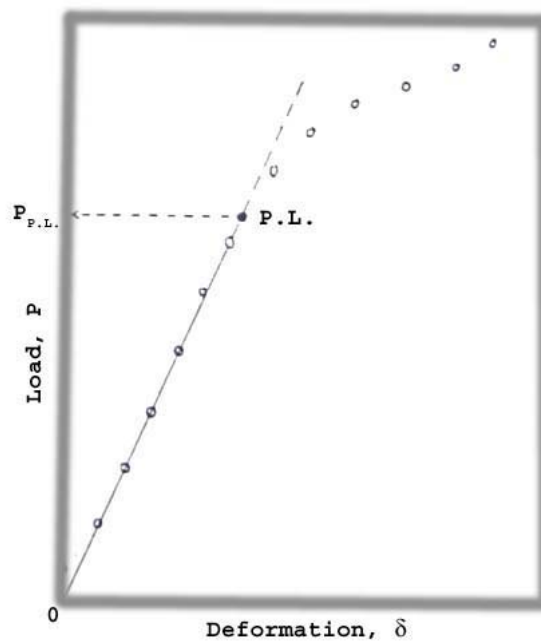


Figure A.4: Graph showing relationship between load and deformation.

## A.6 Shearing Stress Parallel to Grain

- **Size of Specimen**

The shear parallel to grain tests shall be made on 20 by 20 by 20 mm (followed to BS 373 and ISO 3346) (see Figure A.5).

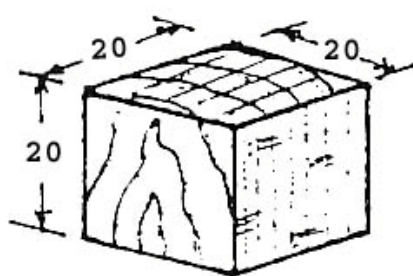


Figure A.5: Shear test specimen.

- **Loading Method**

Use a shear tool similar to that illustrated in Figure A.6 providing a 3.175 mm (1/8 in.) offset between the inner edge of the supporting surface and the plane along which the failure occur. Apply the load to, and support the specimen on end grain surfaces. Take care in placing the specimen in the shear tool to see that the crossbar adjusted so that the edges of the specimen are vertical and the end rests evenly on the support over the contact area (see Figure A.7). Observe the maximum load only.

The load shall be applied continuously throughout the test at a rate of motion of the movable crosshead of 0.6 mm/min.

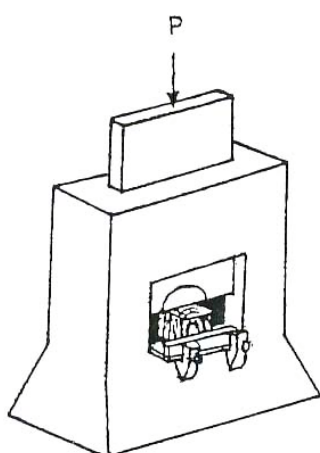


Figure A.6: Shear test.

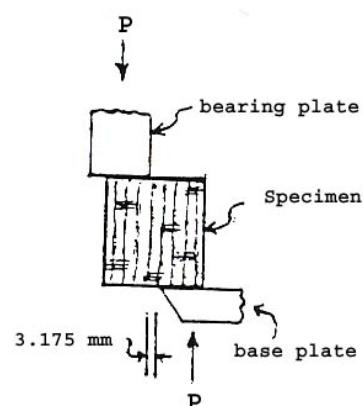


Figure A.7: Shear test showing load application through adjustable seat to provide uniform distribution of load.

- **Specific Gravity and Moisture Content**

See Sections A.2 and A.3.

- **Calculation of Results**

The results are given in term of Ultimate shearing stress parallel to grain,  $\tau$  and can be expressed as:

$$\tau(MPa) = \frac{P_{max}}{A_s}$$

Where,  $P_{max}$  = Maximum load (N or kg)

$A_s$  = Surface area ( $\text{mm}^2$  or  $\text{cm}^2$ )

## A.7 Strength and Stiffness in Static Bending

- **Size of specimens**

The static bending tests shall be made on nominal 20 x 20 x 300 mm specimens. The actual height and width at the center, and the length shall be measured.

- **Loading Method**

Center loading and span length of 280 mm shall be used. Both supporting knife edges shall be provide with bearing plates and rollers of such thickness that the distance from the point of support to the central plane is not greater than the depth of specimen. The knife edges shall be adjustable laterally to permit adjustment for slight twist or warp in the specimen. A bearing block having a radius of curvature of 25 mm for a chord length of not less than 2 in. (50 mm) shall be used.

The load and deflection of the first failure, the maximum load, and points of sudden change shall be read and show on the curve sheet although they may not occur at one of the regular load or deflection increments.

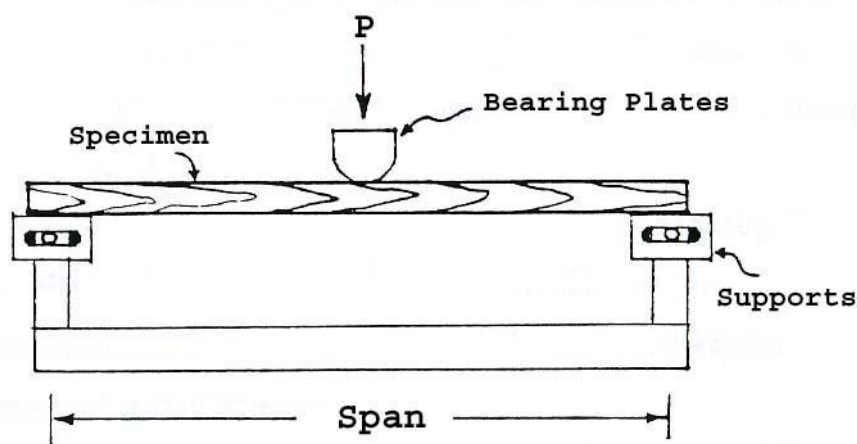


Figure A.8: Static bending test.

- **Description of Static Bending Failures**

Static bending (flexural) failures shall be classified according to the appearance of the fractured surface and the manner in which the failure develops (Figure A.9). The fractured

surfaces may be roughly divided into “brash” and “fibrous” the term “brash” indicating abrupt failure and the term “fibrous” indicating a fracture showing splinters.

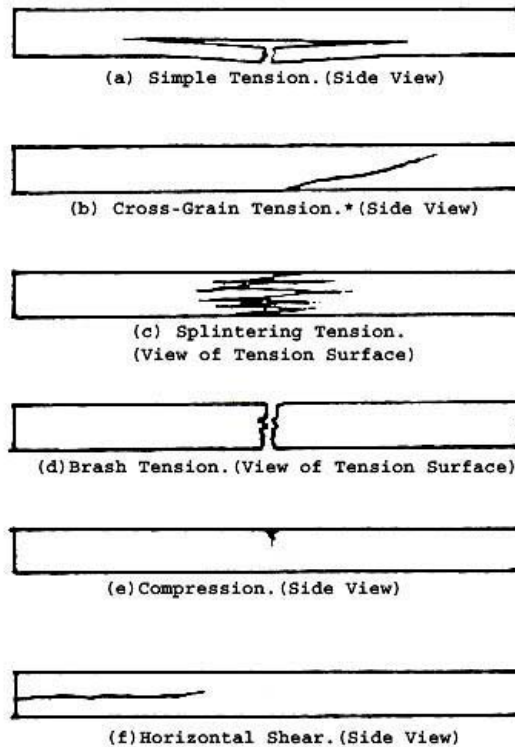


Figure A.9: Types of failures in static bending.

\*The term “cross grain” shall be considered to include all deviation of grain from the direction of the longitudinal axis or longitudinal edges of the specimen. It should be noted that spiral grain may be present even to a serious extent without being evident from a casual observation.

- **Specific Gravity and Moisture content**

See Sections A.2 and A.3.

- **Calculation of Results**

1) *Modulus of rupture (MOR)* -- Reflects the maximum load carrying of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted criterion of strength.

$$MOR = \frac{3P_{max}L}{2bd^2}$$

2) *Modulus of elasticity (MOE)*—Deformations produced by low stress are completely recoverable after loads are removed. When loaded to high stress levels, plastic deformation or failure occurs.

$$MOR = \frac{3P_{pl}L^3}{4\delta_{pl}bd^3}$$

3) *Work to maximum load (W)*—Ability to absorb shock with some permanent deformation and more or less injury to a specimen. Work to maximum load is measure of the combined strength and toughness of wood under bending stresses.

Where

|               |                                               |
|---------------|-----------------------------------------------|
| $P$           | = Load (N or kg)                              |
| $P_{max}$     | = Maximum load (N or kg)                      |
| $P_{pl}$      | = Load at proportional limit (P.L.)           |
| $\delta$      | = Deformation (mm or cm)                      |
| $\delta_{pl}$ | = Deformation at proportional limit (P.L.)    |
| $b$           | = Width (mm or cm)                            |
| $d$           | = Breadth (mm or cm)                          |
| $L$           | = Length of specimen between span (mm or cm). |

## A.8 Hardness

- **Size of specimens**

The hardness test shall be made on 50 x 50 x 50-mm specimens. The actual cross-section dimensions and length shall be measured.

- **Loading Method**

Place the specimen in the hardness tool and use the ball test with a “ball” 0.44 in. (11.3 mm) in diameter for determining hardness (Figure A.10). Record the load at which the “ball” has penetrated to one half its diameter (5.64 mm), as determined by an electric circuit indicator or by the tightening of the collar against the specimen.

The load shall be applied continuously throughout the test at a rate of motion of the movable crosshead of 6 mm/min.

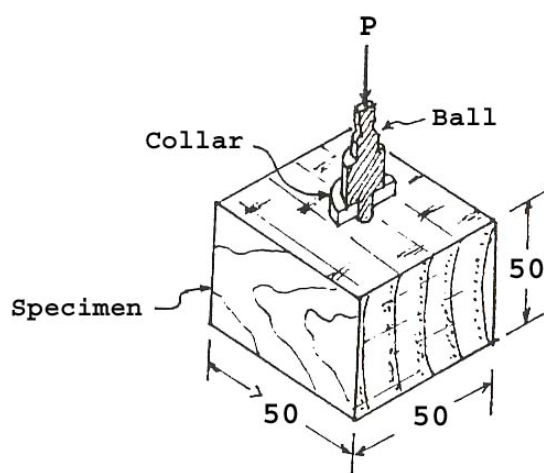


Figure A.10: Hardness test.

- **Specific Gravity and Moisture content**

See sections A.2 and A.3.

- **Calculation of Results**

The hardness will be calculated by:

$$H_m = KP$$

Where

$H_m$  = Hardness at the moisture content (m) during testing

$P$  = Maximum load (N or kg)

$K$  = Coefficient

= 1 if the ball test has penetrated to specimen 5.64-mm depth

= 4/3 if the ball test has penetrated to specimen 2.82-mm depth.

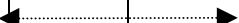
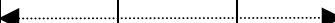
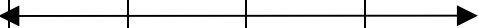
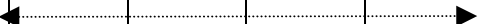
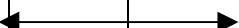
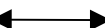
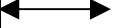
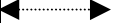
## APPENDIX B

### FULFILLMENT OF OBJECTIVES AND PLANNED ACTIVITIES

#### B.1 Fulfillment of Objectives

| Objectives                                                                                                                                                                                          | Results                                                                                                                           |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| 1. Review literature concerning conventional wood drying and steam drying.                                                                                                                          | 1. The literature review was conducted as planned.                                                                                |
| 2. Determine the drying rates using both air and steam at various conditions.                                                                                                                       | 2. The drying rates of rubberwood using various combinations of superheated steam and air were determined.                        |
| 3. Determine the temperature profiles during the drying period.                                                                                                                                     | 3. The temperature profiles at the center and at the surface of the rubberwood were determined.                                   |
| 4. Determine the acceptability of the dried wood.                                                                                                                                                   | 4. The prong test was used to test the acceptability of wood.                                                                     |
| 5. Determine the optimum drying rate using steam.                                                                                                                                                   | 5. The optimum drying rate was found to be a combination of superheated steam and hot air.                                        |
| 6. Determine the strength of the timber dried using the two methods and compare the results with the commercial product.                                                                            | 6. The shear parallel to grain and the compression strength parallel to grain were determined for the optimized drying condition. |
| 7. Make recommendations to the industry in the form of a report, technical publications etc. to present the possibility of drying rubberwood at reduced cost using the advent of superheated steam. | 7. A technical presentation was completed in the PSU-UNS Conference 2003: Energy and the Environment.                             |

## B.2 Planned and Completed Activities for the First Six Months

| Details                                                 | Aug                                                                                                                                                                      | Sept | Oct | Nov                                                                                                                                                                            | Dec                                                                                 | Jan                                                                                   |
|---------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| <b>1. Project Meeting</b>                               | <br>   |      |     |                                                                                             |  |                                                                                       |
| <b>2. Literature Review</b>                             | <br> |      |     |                                                                                             |                                                                                     |                                                                                       |
| <b>3. Design and Construction of the Drying Chamber</b> | <br>  |      |     |                                                                                                                                                                                |                                                                                     |    |
| <b>4. Test Equipment</b>                                |                                                                                                                                                                          |      |     |                                                                                                                                                                                |  |                                                                                       |
| <b>5. Conduct Steam Experiments</b>                     |                                                                                                                                                                          |      |     |                                                                                                                                                                                |                                                                                     |    |
| <b>6. Maintenance</b>                                   |                                                                                                                                                                          |      |     |                                                                                                                                                                                |                                                                                     |                                                                                       |
| <b>7. Data Analysis</b>                                 |                                                                                                                                                                          |      |     |                                                                                                                                                                                |                                                                                     |  |
| <b>8. Turn in Progress Report</b>                       |                                                                                                                                                                          |      |     | <br> |                                                                                     |                                                                                       |

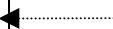
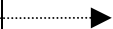
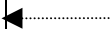
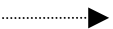
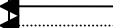
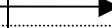
(August 2001 through January 2002)

### B.3 Planned and Completed Activities for the Second Six Months

| Details                                               | Feb | Mar | Apr | May | Jun | July |
|-------------------------------------------------------|-----|-----|-----|-----|-----|------|
| <b>1. Project Meeting</b>                             |     |     | ←→  |     |     | →    |
| <b>2. Literature Review</b>                           |     |     |     |     |     |      |
| <b>3. Design and Construction of the Vacuum Fryer</b> | ←   |     |     |     | →   |      |
| <b>4. Test Equipment</b>                              |     |     |     |     | ←→  |      |
| <b>5. Conduct Steam Experiments</b>                   | ←   |     |     |     |     | →    |
| <b>6. Maintenance</b>                                 |     |     | ←→  |     |     |      |
| <b>7. Data Analysis</b>                               |     | ←   |     |     |     | →    |
| <b>8. Turn in Progress Report</b>                     |     | ←→  |     |     |     |      |

(February 2002 through August 2002)

### B.4 Planned and Completed Activities for the Third Six Months

| Details                             | Aug                                                                                                                                                                    | Sep                                                                               | Oct                                                                                | Nov                                                                                                                                                                           | Dec                                                                                                                                                                        | Jan                                                                                                                                                                        |
|-------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1. Project Meeting</b>           | <br> |  |                                                                                    |                                                                                                                                                                               | <br> |                                                                                         |
| <b>2. Literature Review</b>         |                                                                                                                                                                        |                                                                                   |                                                                                    |                                                                                                                                                                               |                                                                                                                                                                            |                                                                                                                                                                            |
| <b>3. Conduct Steam Experiments</b> |                                                                                       |                                                                                   |                                                                                    |                                                                                                                                                                               |                                                                                                                                                                            |                                                                                         |
| <b>4. Conduct Air Experiments</b>   |                                                                                       |  |                                                                                    |                                                                                                                                                                               |                                                                                                                                                                            | <br> |
| <b>5. Maintenance</b>               | <br> |                                                                                   |  |                                                                                                                                                                               |                                                                                                                                                                            |                                                                                         |
| <b>6. Data Analysis</b>             | <br> |                                                                                   |                                                                                    |                                                                                                                                                                               |                                                                                                                                                                            | <br> |
| <b>7. Turn in Progress Report</b>   |                                                                                                                                                                        |                                                                                   |                                                                                    | <br> |                                                                                                                                                                            |                                                                                                                                                                            |

(September 2002 through January 2003)

### B.5 Planned and Completed Activities for the Fourth Six Months

| Details                             | Feb    | Mar    | Apr    | May | Jun | July |
|-------------------------------------|--------|--------|--------|-----|-----|------|
| <b>1. Project Meeting</b>           |        |        | ↔<br>↔ |     | ↔   | ↔    |
| <b>2. Literature Review</b>         |        |        |        |     | ↔   | ↔    |
| <b>3. Conduct Steam Experiments</b> | ↔      |        |        |     |     | ↔    |
| <b>4. Conduct Air Experiments</b>   | ↔<br>↔ |        |        |     |     | ↔    |
| <b>5. Lab Analysis</b>              | ↔      | ↔      |        |     |     | ↔    |
| <b>6. Maintenance</b>               |        | ↔<br>↔ |        | ↔   |     | ↔    |
| <b>7. Data Analysis</b>             | ↔<br>↔ | ↔      |        |     |     | ↔    |
| <b>8. Turn in Progress Report</b>   |        | ↔<br>↔ |        |     |     |      |
| <b>9. Final Conclusions</b>         |        |        | ↔      | ↔   | ↔   |      |
| <b>10. Complete Final Report</b>    |        |        |        |     |     | ↔    |

(February 2003 through July 2003)

### B.6 Planned and Completed Activities for the Extended Six Months

| Details                             | Aug | Sep | Oct | Nov | Dec | Jan |
|-------------------------------------|-----|-----|-----|-----|-----|-----|
| <b>1. Project Meeting</b>           |     |     | ←→  |     |     | →   |
| <b>2. Literature Review</b>         | ←→  |     |     |     | ←→  | →   |
| <b>3. Conduct Steam Experiments</b> | ←→  |     |     | →   |     |     |
| <b>4. Conduct Air Experiments</b>   | ←→  |     |     | →   |     |     |
| <b>5. Lab Analysis</b>              | ←→  |     |     |     |     | →   |
| <b>4. Maintenance</b>               |     | ←→  | →   |     | ←→  | →   |
| <b>5. Data Analysis</b>             | ←→  |     |     |     |     | →   |
| <b>6. Turn in Progress Report</b>   | ←→  |     |     |     | ←→  |     |
| <b>7. Final Conclusions</b>         |     |     |     | ←→  |     | →   |
| <b>8. Complete Final Report</b>     |     |     |     |     |     | ←→  |

(August 2003 through January 2004)

## **APPENDIX C**

### **DETAILS OF EXPERIMENTAL RESULTS**

#### **C.1 Experimental Results from August 2001 through July, 2002**

The construction of the equipment was completed around the beginning of July, 2002. Preliminary experiments were conducted to select the proper steam temperature and to determine the length of the drying operation. Once the experimental design has been established, testing was done in full scale, with the strengths and physical properties of the dried board to be conducted at the Walailuk University in Nakhon Sri Thammarat.

#### **C.2 Experimental Results from August 2002 through November, 2002**

Experiments had been conducted since the beginning of July, 2002, but many problems had arisen, including short-circuiting of the control box, failure of the steam trap, corrosion of the steam trap, flooding of the drying chamber, low steam temperature, and short-circuiting of the boiler. Many corrective measures had been put into place and are discussed below.

First of all, some water condensed inside of the control box via the thermocouple wires; thus, the holes in the thermocouple panels had been tighten further and the control panel had been moved further away. Next, flooding inside the chamber took place due to the failure of the steam trap. A new steam trap and a bypass valve were installed to release more condensate.

In addition, the temperature inside the vessel dropped significantly from the temperature leaving the heater. Experiments had been conducted so far at 105 and 110°C. Preliminary results indicated that it takes about 24 hours to dry a piece of 1" lumber at 110°C from 90% db to 13% db. During testing, a **moisture content meter** was purchased to measure moisture and various location of the lumber. It was found that the moisture content varied significantly at different locations. In order to reduce the moisture content to less than 20% db, the lumber must be turned. This may be due to the differences in steam temperatures entering from the top and bottom of the chamber from heat loss of the pipes. Moreover, the location of the perforated steam pipes were not exactly opposite of each other, with the top being off-centered to allow for the hoist of the metal rack and load cell.

Another modification that was made was adding a gas-fired heat-exchanger in front of the electrical heat-exchanger. It was proposed that this would increase the quality of the steam and reduce energy consumption; however, after testing, there was no significant temperature increase inside of the drying chamber. Therefore, it was concluded that the heat loss from the chamber may be very substantial and more **insulations** were placed around the chamber and at the cap.

After the adjustments had been made, experiments were then prepared to be conducted at the following conditions: temperatures of 105, 110, and 115°C and at 2, 4, 6, 10, 16, and 24 hours. Unfortunately, only data for 2 and 4 hours have been collected when the boiler went down. The boiler had to wait for technicians from Bangkok which slowed down the experiments for several weeks.

Finally, from Figures C.1 through C.3, it can be seen that the dried lumber showed brown stains. These stains might have resulted from the borax (boron compounds) that was used to treat the lumber prior to drying. Testing with untreated lumber is being conducted to check for this problem. In addition, some warping resulted from the uneven heating (more heat from the bottom) and the lumber may have to be turned to reduce this effect. Another option is to “shape” or “press” the wood after drying to straighten it out. Preliminary tests have shown that pressing significantly reduce the percentage warping of the lumber.

Thus far, many problems had arisen within the months of this report, but modifications were made to account for these dilemmas. The installation of a new, smaller boiler had been discussed, but the cost was extremely expensive reaching 100,000.00 baht. In addition, a **relative humidity meter** had been purchased to check for saturation inside the chamber. The new equipment arrived within the next few weeks; however, this equipment was never installed within the time frame of the project due to suggestions that it would slow down the experimental procedures substantially.



Figure C.1: A dried piece of lumber laying flat on the storage chamber



Figure C.2: A picture showing the lumber lying on its thickness.



Figure C.3: A close-up of the lumber showing stress cracking (which may be due to the extreme heating from the bottom) and the brown stains.

### **C.3 Experimental Results from December 2002 through January, 2003**

The boiler was back on line toward the end of December and experiments resumed in January. From the recent experiments and analysis, there was a large deviation between the temperature of steam leaving the perforated pipes and the temperature inside the chamber as a whole. The steam temperature leaving the electric heater was about 180°C; however, as it enters the chamber and leaves the perforated pipe, it was about 140°C. Still, due to the high humidity inside the chamber, the temperature settled around 110°C and an absolute pressure of 1 atm. Therefore, it was necessary to reduce the moisture level inside the chamber to be able to remove the bound water from the rubberwood.

In order to test this hypothesis, a relative humidity probe/meter was purchased. However, this equipment requires drilling the wall of the chamber and inserting the probe. This installation was very difficult since it required removal of several layers of insulations and a metal sheet covering the chamber. Therefore, the installation had been postponed.

To handle the problem of high humidity inside the chamber, the team suggested blowing hot dry air in place of steam for about one hour. This final period of drying may be sufficient to remove the necessary portion of the bound water. Tests were conducted to test this hypothesis.

Furthermore, the team had concluded that using the boiler from the Department of Chemical Engineering was not energy efficient. One 24 hours experiment usually used up an entire tank of gas. Therefore, a design of a steam recycling system was underway. Steam leaving the vent would be sent to a new, smaller boiler which was being designed. The new boiler would be built with a minimum budget. A previous estimate from a local vendor priced the boiler at well over 100,000.00 baht. However, the new boiler that was being designed would be much cheaper, perhaps costing around 50,000.00 baht. Until this boiler is completed, experiments would continue to be done using the large boiler. Although the results obtained so far have not been positive (except for a few instances), improvements were being made.

#### **C.4 Experimental Results from February 2003 through April, 2003**

Since the beginning of February, many tests had been conducted involving the hybrid drying with air and steam to reduce the humidity inside the chamber after a certain period of drying. First, steam was purged for 6 hours at 110°C and followed by hot air at 80°C for one hour. The cycle was continued until a satisfactory reduction of moisture content to the desired value of about 12% w.b. was reached. Two other hybrid cases that were studied includes: (1) steam for 4 hours followed by hot air for one hour and (2) air for 6 hours followed by steam for 1 hour. Three tests conducted for each operation.

From the experiments, it was shown that it took about 35 hours to completely dry the wood depending on the initial moisture content. Even though the woods obtained were placed in refrigerator while waiting to be dried, their initial moisture content often varies 5 to 10%. Therefore, there was no noticeable difference between the first and the second case, while the first two cases appear to dry faster than the third. In addition, the wood that had been dried often had cracking which sometimes originated from a minor crack that can be seen before drying. As the drying continued, the cracks grew even larger. Furthermore, warping of the wood occurred as the amount of heat (temperature reaching the wood surface) from the top and bottom nozzles differed. The top nozzles did not impinge straight above the wood, but from an angled position due to the shaft of the metal rack. Moreover, woods placed on the rack were nearer to the bottom nozzles.

To deal with these problems, a wood straightener apparatus (shown in Figures C.4 through C.7) was designed and constructed to allow the woods to be more centrally located within the chamber and for the clamps to prevent warping. Preliminary tests showed that the apparatus had significantly reduced warping. The next series of tests that were conducted utilized this apparatus. The best results using the hybrid steam-air cycle would be further analyzed and a comparison would be made with the hot air drying method. Testing of the physical properties of the woods using these conditions were to be conducted within the next 2 months, but actually a few months behind schedule. Analysis of data continued with a summary of the experiments expected by the middle of July and the final report completed by the end of that month.



Figure C.4: Roller designed to straighten wood and reduce cracking.

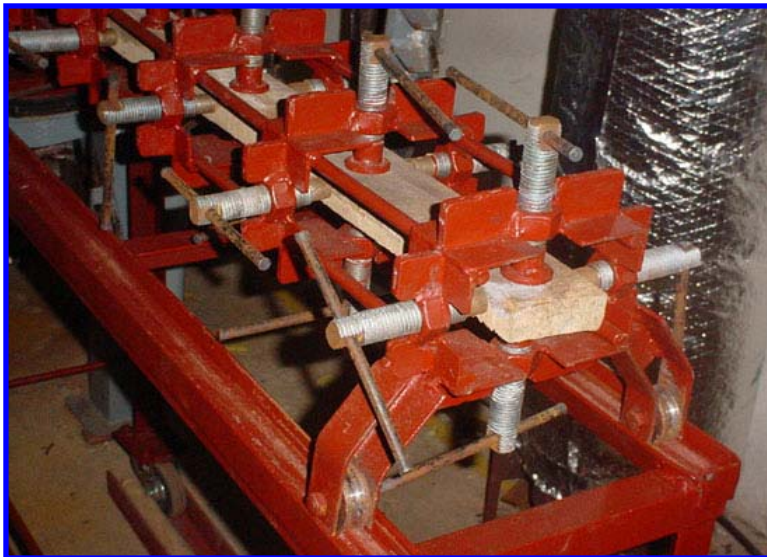


Figure C.5: The straightener apparatus showing clamps and tighteners.



Figure C.6: Side view of the straightener apparatus.

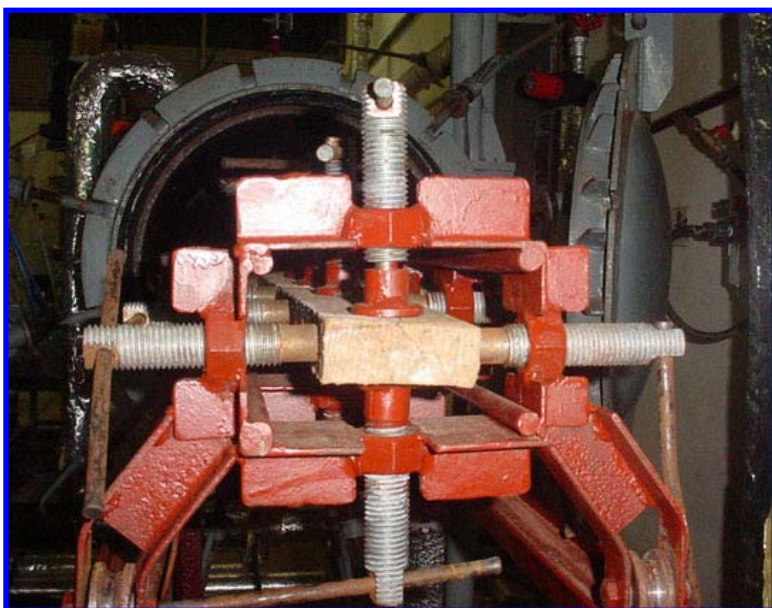


Figure C.7: Front view of the straightener apparatus.

### C.5 Experimental Results from May 2003 through January, 2004

Since the beginning of May, more experiments had been conducted to test the repeatability of the results. These results also underwent the Prong Test. Results showed that air impingement drying alone maintained excessive stress build up, while the combination of steam and air drying (6:1 ratio) passed the Prong Test. Studies at 4:1 steam to air ratio, however, yielded unsatisfactory results, perhaps to due the exceedingly fast drying during the initial stages. Literature reviews suggested that conditioning of the woods may be required for those that dry too rapidly.

As a result, steaming during the initial stages of drying was increased to slow down the rate of moisture transport and to reduce the moisture gradient. Also, air drying was increased after the moisture content of the wood was reduced below fiber saturation point of about 25% dry basis for rubberwood. Superheated steam at the low moisture content values resulted in an insignificant amount of water removal, thus, it was not energy efficient. Refer to Table 5.3 for the optimum drying schedule. Hence, this methodology was tested and satisfactorily passed the Prong Test.

Moreover, in order to dry more than piece of wood at a time, a new straightener apparatus was built. This equipment was used to clamp 3 pieces of wood per experiment. Two sets of wood have been sent for physical testing at Walailuk University. Due to the lengthy testing procedure (including several weeks of conditioning), results may not be available until early January.



Figure C.8: Top view of board Grade C after drying at optimum condition.



Figure C.9: Front view of the same piece of board.

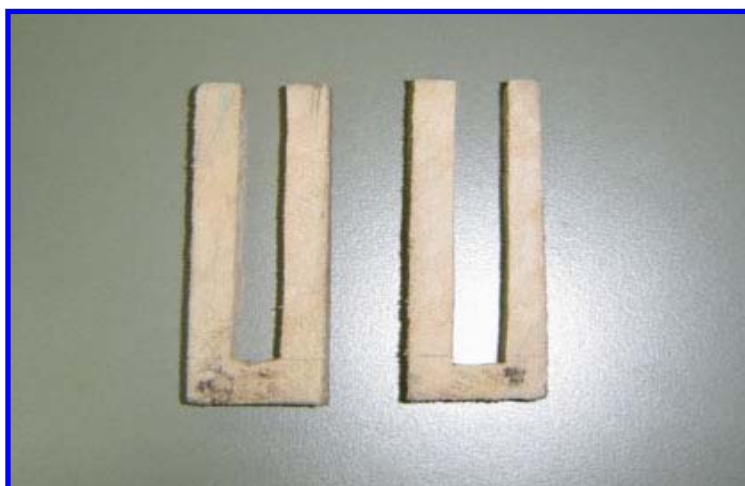


Figure C.10: Two pieces of samples after the prong test showing no excessive stress buildup after drying.



Figure C.11: Dried lumber using the multiple-pieces wood clamp prior to being sent for mechanical analysis.

In addition, to alleviate uneven heat transfer to the wood surface, the upper steam impingement pipe was repositioned to equalize the amount of heat transfer from the top and bottom of the wood. However, due to unforeseen circumstances, problems with the boiler developed, specifically, the heating element of the boiler was malfunctioning leading to a drop in pressure of the boiler. Technicians from Bangkok were contacted to repair the system, but the response was slow and non-cooperative. Finally, the technicians arrived, cleaned, and repaired the boiler at a substantial cost of more than 51,000.00 baht. Fortunately, the Department of Chemical Engineering covered over 70% of the charges for repair, and the project only had to assist with only 27% of the cost.

Still, not all of the mechanical properties test could be completed by the end of January as had planned, even though the samples have all been sent to Walailuk University. The Lloyd Universal Testing Machine went down and needed repair. Even by the end of January, the repair has yet to be completed. Therefore, only two major mechanical properties have been determined thus far, the shear parallel to grain test and the compression strength parallel to grain test have been conducted. The compression perpendicular to grain, the hardness, and the static bending tests (Modulus of Elasticity (MOR) and Modulus of Rupture (MOE)) have not been conducted, while the prepared specimens wait for testing in the conditioning chamber.

Nonetheless, the analysis of data and the report with a summary of the experiments have been completed and will be sent to the readers by the beginning of February. Please note that the results of the three remaining tests will followed as soon as possible.

**APPENDIX D**

**PAPER PRESENTED AT**

**THE PSU-UNS INTERNATIONAL CONFERENCE 2003:**

**ENERGY AND THE ENVIRONMENT**

**PSU-UNS International Conference 2003**  
**“ENERGY AND THE ENVIRONMENT”**  
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## SUPERHEATED STEAM DRYING OF RUBBERWOOD

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### ABSTRACT

An elliptical vessel 1.2 m long and 0.5 m in diameter drying chamber was constructed and injected with superheated steam to test the effect of superheated steam on the drying of rubberwood. The dimensions of the wood board were 1m x 1 in. x 4 in. The piece of board was impinged with alternating cycles of superheated steam and hot air at ratios of 6:1, 4:1, and 1:6 hrs until the moisture content was less than 15% d.b. The conditions inside the drying chamber were 110°C and ambient pressure. Pure superheated steam and pure hot air were also used for comparisons. The drying rate and the temperature profile of each of the processes were determined. Initial acceptability of the dried wood was conducted using the prong test and visual inspection.

Results showed that if the drying rate was too fast, the dried wood did not pass the prong test due to stress buildup. Therefore, drying the wood for 6 hours using superheated steam followed by hot air for 1 hour alternately produced the most acceptable results. The reduced drying time (less than 2 days) compares favorable to the conventional process of 7 – 8 days using hot air with intermittent steam injections. The superheated steam process presents a substantial saving in energy cost and operating cost compared to the conventional method. Additional studies will be conducted to test the color, hardness, shear bending, modulus of elasticity, and strength of the wood.

### KEYWORDS

Rubberwood, Drying, Superheated Steam, Steam-Impingement, Impingement Drying

### 1. INTRODUCTION

Wood from the rubber tree is the major source of timber in Southern Thailand. The tree (*Hevea brasiliensis*) is typically harvested between 25 and 35 years of its growth so that the diameter is less

than 200 mm (according to a source from Asia Plywood Factory<sup>1</sup>). It is delivered in short lengths (approximately 1 meter long) and, after sawing, has to be glue laminated to get useful plank dimensions.

For glue lamination to be effective, the timber must be dried. However, if the rubberwood is dried too quickly, it will split, crack, warp, cup or check due to unrelieved moisture stresses. Hence, the drying of rubberwood requires an optimum drying rate, while reducing power consumption of the process.

Timber drying is traditionally carried out using warm air. The process may be carried out in a kiln or in “stacks” of “packets” in the open air. The latter process is largely uncontrolled so that the sun’s radiation or a prevailing wind can set up moisture stresses that may distort the wood. Rubberwood is usually arranged in stacks and dried in a 400-600 m<sup>3</sup> chambers at temperatures of 80-100°C. The drying time varies from 12 to 16 days depending on the thickness of the lumber. After several days, a mist of water droplets is introduced into the drying chamber (along the side walls) and is circulated with fans. The process helps to maintain a good moisture distribution within the boards and to reduce moisture stress by temporarily increasing the relative humidity in the chamber. If the temperature of the dryer is too high, the moisture stress may lead to cracking due to large moisture gradient within the board. However this method of humidity control is generally somewhat crude and inefficient. As a consequence, the desired result is not always achieved and energy usage is seldom optimal.

In areas of high humidity, air seasoning is very slow and fungi (or even insects) attack the wood. Generally, the attack produces unsightly colors on the surface but does not significantly reduce the strength of the timber. However, the discoloration significantly degrades the appearance of the product

<sup>1</sup> Asia Plywood Factory, Phetkasem Road, Moo 1, Muang Yala, Yala, Thailand 95000

for furniture or finishing work.

Anti-sapstain chemicals have been widely used to control fungal attack during air-seasoning. To some extent, the added expense of applying chemicals offsets the negligible energy costs in the process. Kiln-drying gives much more control over the drying process; however, it is at the expense of the energy needed to dry the wood and to circulate the air. In addition, some anti-sapstain chemicals are still required wherever long drying processes enhance the incubation of fungal spores.

## 2. LITERATURE REVIEW

In terms of fundamental knowledge of the drying process, heat and mass transfer at the surface are known to determine the initial rate of drying. Later, after the surface water is removed, the rate of drying is determined by the rate at which moisture can diffuse to the surface of the wood. Thus, the initial rate of drying gradually decreases until the cellulose of the wood comes to equilibrium with the drying air above it. The initial high rate can be increased by the following:

1. Reducing the humidity of the drying medium
2. Increasing its turbulence over the surface

The rate of moisture diffusion through the wood can be increased by

1. Raising the temperature of the wood
2. Ensuring that all moisture is evaporated from the surface exposed to the drying medium
3. Ensuring that the bordered pit structure between the cells is open

If the temperature is raised too high, (or the operating pressure is reduced), the water in the pores of the wood reaches its boiling point. The sudden phase change usually destroys the cell structure. *Ptylosis* is the process by which the lignins in the wood harden and seal the bordered pit structure. It starts as soon as the tree is cut. In general, steaming the wood with wet saturated steam keeps the pit structure open. If this is followed by drying, very high rates can be achieved without damage occurring from the moisture stress. This is because moisture is able to move freely between the cells.

Superheated steam can also be used as the drying medium. Superheated steam may be produced by dropping the pressure at the end of the steaming operation or by the vapor-recompression of low quality steam coming out of another process. Because of the reduced opportunity for tannins to

oxidize, the color of the wood is maintained through steam drying.

Douglas (1994) used steam to dry paper. He found that for paper made from mechanicals pulps, drying in superheated steam produced better bonded sheet. The added strength was accompanied by a lower scattering coefficient and improved surface properties. Moreover, the drying rate achieved using superheated steam was found to be about twice as high as that achieved with air.

Pang and Dankin (1999) studied the drying rate and temperature profile for superheated steam vacuum drying versus moist air-drying of softwood lumber (*Pinus radiata*). They found that the superheated steam produced a significantly faster drying rate than the hot moist air.

Aly (1999) replaced the conventional air-drying of milk powder with superheated steam drying. In his work, Aly operated the superheated steam in a recycle mode where evaporated water is purged and compressed in a two-stage mechanical vapor compressor (MVC). The purged compressed steam is used to boost the superheated steam temperature from the circulating exit up to the required inlet temperature of the dryer. This process helped to reduce the energy consumption of the plant.

Furthermore, Li, et al., (1999) concluded that superheated steam produced a faster drying rate for tortilla chips at elevated temperatures compared to air-drying. For the food material, steam-drying did not cause severe oxidation and burned regions like the air did. Hence, it may be possible for superheated steam at intermediate to high temperature (140-180°C) to not cause much discoloration of the lumber.

Oil and other heat transfer fluids can also be used to convey heat into the wood. If the heating is followed by pressure reduction, water will vaporize as it leaves the wood and can be easily separated from the heat transfer fluid, thus allowing the fluid to be recycled.

Microwaves have also been used to heat the wood structure while the pressure is reduced to evaporate the water. However, this must be very carefully controlled if the phase change inside the wood is not to be destructive. In general, only exotic woods in the form of veneers are commercially dried using microwaves.

All of the processes listed have been tried and operated. Several are the basis of patents while others are in commercial use.

## 3. EXPERIMENTAL SETUP

Fig. 3.1 presents a schematic diagram of the experimental setup, and Fig. 3.2 depicts the actual equipment constructed. Steam driven from a 10 bar capacity boiler is heated into superheated steam using a 2 kW electrical heater prior to being

injected into a 1.8 m<sup>3</sup> drying chamber. The rubberwood board is placed on a clamped rack support inside the chamber. After entering the chamber, the steam is impinged from a pair of perforated pipes located above and below the wood board. The pipes distribute the steam evenly inside the chamber (a sparging unit). A small vent releases the evaporated moisture and excess steam, and the condensed vapor leaves the chamber as liquid water through the steam trap. Some of the exiting vapor can also be passed through a vapor recompression stage (not shown) for recycling.

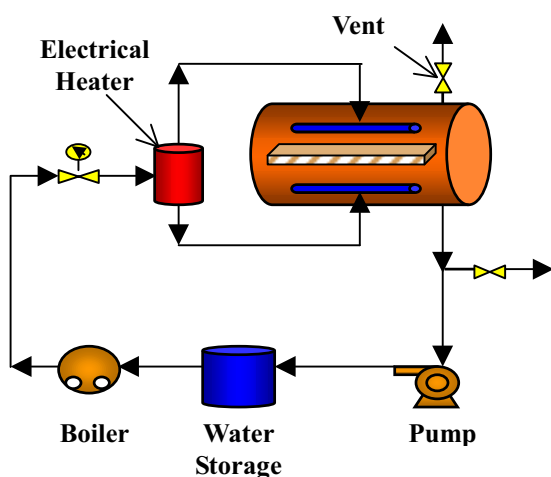


Fig. 3.1 Schematic of superheated steam drying operation.



Fig. 3.2 Actual equipment setup.

### 3.1 Wood samples

Rubberwood boards with dimensions of 1 m long x 4 in. wide x 1 in. thick were taken from Rutthapoom Parawood. The initial moisture content was approximately 50% dry basis (d.b.).

### 3.2 Drying conditions

Table 1 lists the various conditions used in this study.

### 3.3 Drying rate experiments

The drying rate for each condition was obtained by measuring the weight of the wood board after

each period of drying. The initial moisture content of the wood was determined by cutting a small piece of the board and drying it in a 60°C oven for 24 hours (modified from AOAC, 1990).

Table 3.1 Experimental Conditions

| No. | Superheated Steam (110°C)* | Hot Air (80°C) |
|-----|----------------------------|----------------|
| 1   | Continuous                 | -              |
| 2   | 6 hours                    | 1 hour         |
| 3   | 4 hours                    | 1 hour         |
| 4   | 1 hour                     | 6 hours        |
| 5   | -                          | Continuous     |

\*Temperature inside the chamber

### 3.4 Temperature profile experiments

Thermocouples were placed at the surface of the wood and at the center of the wood for temperature profile experiments. Temperature readings were taken using a digital reader.

### 3.5 Prong test

Initial acceptability of the dried wood was determined using the Prong Test. For stress free drying the prongs should ideally remain straight or curve out slightly. If the prongs pinch in, then stress is present (Rosen, 1987). Prongs that curve inwards represent a casehardening scenario, while those that curve outwards and remain bent outward represent reverse casehardening scenario. A half-inch thick cross section of the wood was taken and cut into U-shape. If the ends of the U bend toward each other slightly, the wood was deemed unacceptable due to excessive stress buildup.

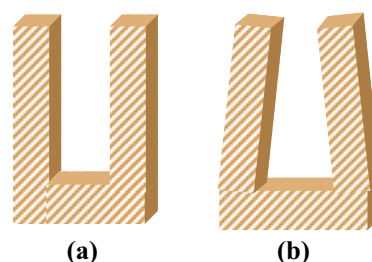


Fig. 3.3 Prong test showing (a) acceptable piece of board and (b) unacceptable piece of board with excessive stress buildup (casehardening scenario).

### 3.6 Data analysis

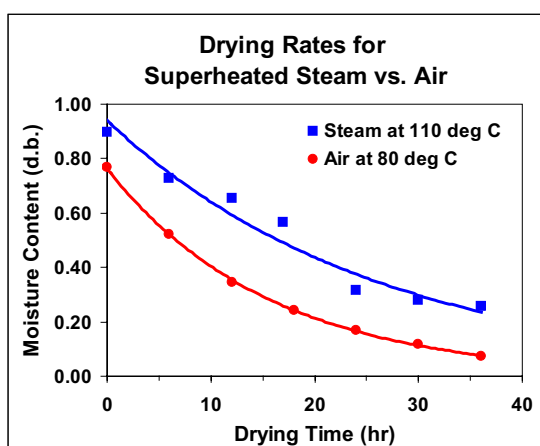
The experimental data were averaged and analyzed using Microsoft® Excel 2002. All experiments were performed at least in duplicate.

## 4. RESULTS AND DISCUSSION

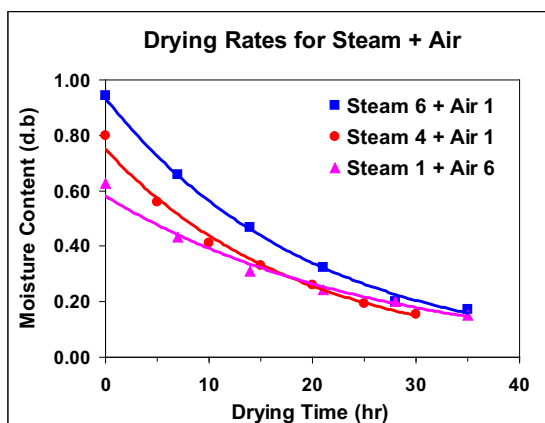
### 4.1 Drying rates

Fig. 4.1a and 4.1b illustrate the drying curves for superheated steam drying at 110°C and hot air

drying at 80°C. The y-axis represents the moisture content in dry basis (d.b.) and the x-axis is the drying time in hours (hr). The curves depict the general drying curve which consists of 3 distinct periods: (1) the initial heating period, (2) the constant drying period, and (3) the falling rate period. The initial period, characterized by a rapid increase in temperature of the wood from room temperature to the boiling point of water, is not clearly seen below since the time frame is small compared to the total drying time. The rapid increase in temperature is shown in Fig. 4.2.



(a)



(b)

Fig. 4.1 (a) Drying rates of superheated steam at 110°C vs. hot air at 80°C. (b) Drying rate at various combinations of superheated steam and air.

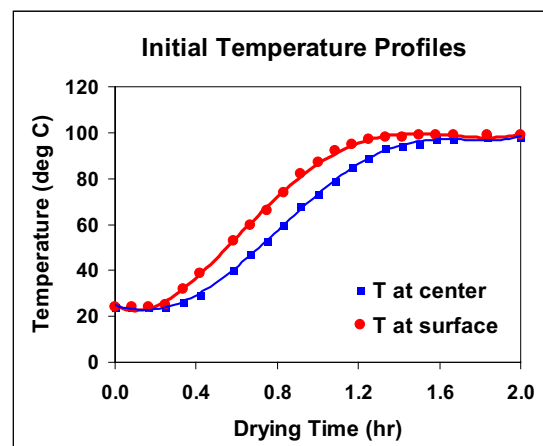
From Fig. 4.1a, the drying rates of both the superheated steam and the hot air are much faster than the conventional methods which take up to 8 days for the moisture content of the wood to reach the acceptable value of less than 0.15 d.b. This is due to the impingement technique which causes rapid heat transfer to the surface of the wood and

rapid moisture loss from the wood. Moreover, the constant rate of drying for hot air is faster than that of superheated steam case due to lower humidity that developed inside the chamber. After 25 hr of drying, the rate of water loss for the superheated steam case is quite low due to the high amount of water vapor that exists inside the chamber. Since the rate of water vapor leaving the vent and the rate of vapor condensation are less than that of the entering steam, the humidity inside the chamber remained high causing the removal of the bound water to be very difficult. Hence, it is essential that the humidity of the chamber be reduced in order to decrease the final equilibrium moisture content (EMC) of the rubberwood.

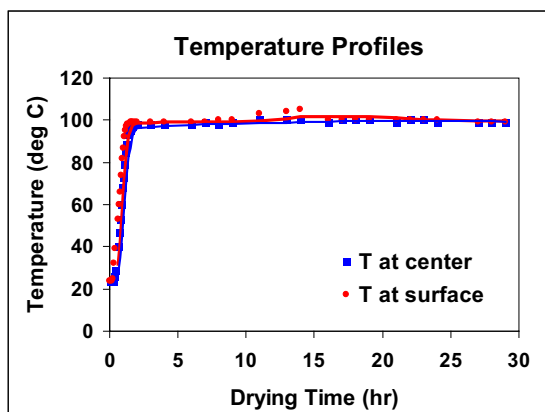
Fig. 4.1b shows that the moisture content of the rubberwood can be reduced to less than 0.15 d.b. using a combination of steam and hot air. Even though the case for 6:1 steam to air ratio scenario began at a higher initial moisture content, the slopes of the drying curve is very similar to that of the 4:1 steam to air scenario. Nevertheless, the former case is preferred over the 4:1 and 1:6 cases, because it passed the prong test (see Table 4.1).

#### 4.2 Temperature profile

Fig. 4.2a and 4.2b show the temperature profiles (°C) at the center and at the surface of the wood as a function of drying time (hr).



(a)



(b)

Fig. 4.2 Temperature profiles at the center and at the surface of the wood (a) after 2 hr and (b) after 30 hr of drying. Superheated steam at 110°C and 4:1 steam to air ratio was used.

As mentioned previously, the temperature at each point increase rapidly until the boiling point of water is reached (slightly lower than 100°C due to dissolved solutes in the water). Fig. 4.2a illustrates that the temperature at the surface increases faster than at the center. The temperature at the surface reached the boiling point after 1.2 hr of drying, while it takes about 1.6 hr of drying for the temperature at the center to reach the boiling point.

Furthermore, even after the 30 hours of drying, the temperature at the center and at the surface of the wood remained near 100°C indicating that there is still some water evaporation occurring. It would take complete drying of the wood surface (negligible amount of water remaining) before the temperature begins to increase toward the temperature of the superheated steam inside the chamber.

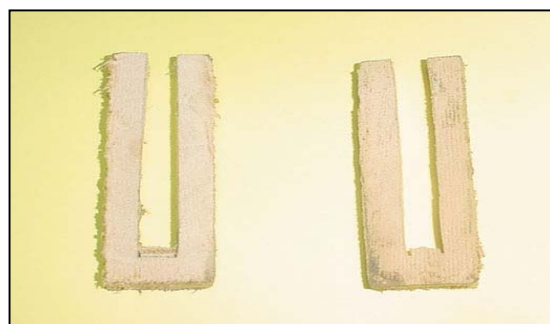
#### 4.3 Physical analysis

Table 4.1 below shows the results from the prong tests for cases in which the acceptable moisture content of 0.15 d.b. was reached. The ratios of Steam 6: Air 1 represents a drying scheme of 6 hours of steam, followed by 1 hour of air drying. The scheme is repeated alternately until the equilibrium moisture content was reached. Even though the Air Only, the Steam 4: Air 1, and the Steam 1: Air 6 cases reached the acceptable moisture content, their rates of moisture loss may have been too rapid, causing excessive stress buildup which led to their failing the prong test (see Fig. 4.3).

Table 4.1 Results of prong test.

| Condition  | EMC less than 0.15 d.b. | Passed Prong Test |
|------------|-------------------------|-------------------|
| Steam only | No                      | -                 |

|                |     |     |
|----------------|-----|-----|
| Air only       | Yes | No  |
| Steam 6: Air 1 | Yes | Yes |
| Steam 4: Air 1 | Yes | No  |
| Steam 1: Air 6 | Yes | No  |



(a)

(b)

Fig. 4.3 (a) Hot air dried wood showing slight bending of the prong. (b) Superheated steam 6: air 1 case showing the lack of stress buildup.

Moreover, physical testing of the dried boards will have to be conducted, such as testing for hardness, toughness, strength, and color. Finally, the optimum steam to air ratio and the appropriate drying schedule will have to be determined in order to minimize the drying time and maximize the physical properties of the wood.

#### 4.4 Energy saving potential

From preliminary studies, superheated steam drying presents a significant energy savings in terms of drying time. In traditional wood drying operations in Thailand, boilers are used to generate steam which is then fed into heating coils for the heating of hot air that is blown into the chamber by compressors. The fuel sources for the boiler are wood chips and wood dusts that are inexhaustible byproducts of the wood cutting process.

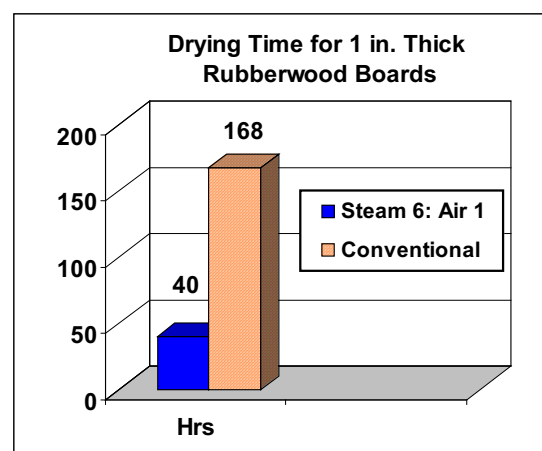


Fig. 4.4 Drying time comparison between superheated Steam 6: Air 1 scenario and conventional drying for 1 in. thick rubberwood board. Fig. 4.4 illustrates the potential energy savings

offered by the generation of superheated steam using heating coils of high pressure, high temperature steam or even electrical coils in terms of drying time. For the superheated steam plus air drying, the process time is approximately 40 hours (less than 2 days), while the conventional process takes about 168 hours (7 days). Therefore, this technique can reduce the time of drying operations by as much as 75%.

## 5. CONCLUSIONS

The superheated steam impingement drying of rubberwood was suggested as an alternative to conventional drying. A combination of superheated steam and air drying produced substantially reduced drying time; however, only the case of 6 hours of superheated steam followed by 1 hour of air drying passed the prong test which checked for excessive stress development. With further optimization and testing for strengths and toughness, the drying time for 1 in. thick boards can be reduced from 7 days to less than 2 days.

## ACKNOWLEDGEMENT

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