Comparative Steam Bending Characteristics of Some Planted Forest Wood Species in Malaysia

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The bending performance of wood is important for its application in furniture, and it is one of the criteria used to assess the suitability of a particular wood species for furniture. In this context, the steam-bending and surface roughness characteristics of four forest plantation wood species were evaluated. One batch of wood specimens were subjected to both surface roughness experiments using the stylus and toluene spread methods, while another batch of the wood specimens were subjected to steaming, clamped, and bent using a circular shape mold. The instantaneous spring-back was measured after 10 days, while the spring-back over time was measured from days 15 to 65. The surface roughness experiments showed that the *Hevea brasiliensis* had the lowest surface roughness, followed by the *Eucalyptus pellita*, *Acacia mangium*, and finally *Revotropix paulownia*. In terms of the bending performance, it was found that only the *H. brasiliensis* achieved the threshold 95% satisfactory level based on visual ranking. Furthermore, the wood species also recorded the lowest spring-back, both instantaneous and over-time, to register the best bending performance. On the other hand, *R. paulownia* had the worst bending performance, primarily due to its low density.

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INTRODUCTION

The sustainable supply of wood for the large wood products and furniture manufacturing industries in Malaysia is a major concern among manufacturers and policy makers. Malaysia's wood products and furniture exports, which stands at RM 22 billion per annum for the last few years, continue to struggle in light of the raw materials supply crunch coupled with the increasing labor cost due to its continued dependence of foreign contract workers (Ratnasingam *et al.* 2018; MTIB 2021). In fact, the severity of the raw materials supply problem became apparent when the export target for wood products and furniture by the year 2020 had to be halved to RM 25 billion from its original figure of RM 53 billion as stipulated by the National Timber Industry Plan (NATIP), which was formulated in 2009 (Ab Latib *et al*. 2022).

As the supply of wood raw materials from the natural forests has declined over the years under the principles of sustainable forest management (SFM), the need for an alternative wood supply from planted forests has become increasingly urgent. Although

Malaysia's experience and track record in forest plantations, which began in the early 1980's, has not been a glowing success, the country's need for forest plantations became increasingly pressing in the late 1990's. The establishment of the Forest Plantation Development Sdn. Bhd. (FPDSB), a special-vehicle company, under the administration of the Malaysian Timber Industry Board (MTIB) was aimed at facilitating forest plantation establishment throughout Peninsular Malaysia (MTIB 2021). A few selected fast-growing tree species, with rotations of 15 years were eligible for financing under the program. As of 2021, a total of 130,000 ha of forest plantations has been established through this program. The harvest of the first rotation is expected in mid-2022. In East Malaysia, forest plantation programs have been more aggressively pursued due to availability of land, and as of 2021, 576,000 hectares have been established as forest plantations (MTIB 2021). In fact, compared to Peninsular Malaysia, where land availability and land-related matters are more limiting, the East Malaysian states of Sabah and Sarawak appear to have been more successful in establishing forest plantations on a much larger scale. East Malaysia accounts for almost 75% of all forest plantation activities throughout the country (MTIB 2021).

Among the fast-growing tree species planted, the three most prominent species that appear to have gained acreage are rubber (*Hevea brasiliensis*), *Eucalyptus pellita*, and *Acacia mangium.* Another important yet not too established fast-growing tree species that is fast gaining acreage is *Revotropix paulownia*, which appears to be promising as a successful fast growing tree species candidate (Ab Latib *et al.* 2020). Table 1 shows the current planted acreage of these fast-growing forest tree plantation species throughout Malaysia.

Although *H. brasiliensis* cultivation has been undertaken in Malaysia since the early 1990's, this tree crop has been planted primarily for latex or natural-rubber production, rather than its wood. The total area under rubber cultivation for latex production stood at 1.01 million hectares in 2021 (MTIB 2021). Under the existing legislations, this land area under rubber cultivation is not directly considered as forest plantation. On the other hand, rubber cultivation for the purpose of wood production using the latex-timber clones (LTC) began only in the late in mid-2000's, which contributes to the total area of forest plantations in the country.

Table 1. Total Area of Forest Plantation Tree Species in Malaysia

No.	Species	Total Cultivated Area (ha)
1	*H. brasiliensis*	512,000
2	*E. pellita*	32,700
3	*A. mangium*	327,510
4	*R. paulownia*	19,800

+ Data from Ratnasingam *et al.* (2021)

The compelling arguments in favor of forest plantation establishment is the fact that these forest plantation trees species are forecasted to yield at least 200 m^3 of wood per hectare. This is much higher than the yield of 60 m^3 per hectare recorded previously for the rubber plantations, planted primarily for latex production (Ratnasingam *et al.* 2021). Against this background, with an annual projected harvest of almost 2 million m^3 of usable wood supply, this will alleviate the problems associated with the inconsistent supply of wood materials for the large wooden products and furniture manufacturing industry in Malaysia (Ratnasingam *et al.* 2021).

Despite the forecasted significant supply of forest plantation wood, the level of acceptance of this wood supply, especially by the furniture manufacturing industry, remains uncertain. This is particularly owing to that fact the wood species plays an important role for the success of value-added wood products, including furniture, especially among the discerning customers from Europe and North America (Ratnasingam *et al.* 2007). Although information on the mechanical properties of these plantation wood species is available (Sahri *et al.* 1998; Lim *et al.* 2011; Nordahlia *et al.* 2013; Ab Latib *et al.* 2020; Japarudin *et al.* 2021), information on the specific working properties of these wood species remains limited. The surface smoothness and bending properties of wood are critical, as they are important criteria for the success of any wood species for furniture application (Ratnasingam *et al.* 2007). This fact is attested by the success of rubberwood (*H. brasiliensis*) and beech (*Fagus sp.*), which are important raw materials for furniture manufacturing, attributed to their good working properties. Surface smoothness has important implications for the gluing and coating characteristics of the wood species, while the use of bent wood components imparts a high aesthetic value to the piece of furniture (Ratnasingam *et al.* 2007).

In fact, the bending of wood is an important value-adding process in furniture making, especially for chairs and tables. Bending of wood can be accomplished through steam treatment, kerf bending, laminated bending, as well as heat treatment using microwave and high-frequency technology (Sandberg and Johansson 2005; Ozarska and Daian 2010). However, the most consistent results for bending of wood are achieved through steam bending, and therefore this process has become the most common method for wood bending in the furniture manufacturing industry in many parts of Asia (Kubojima *et al.* 2000; Gašparík and Barcík 2014).

Steam Bending of Wood

Bending wood allows the creation of curved components and objects, which can otherwise be achieved through sawing or machining, which results in waste. Generally, curved objects are stronger and stiffer than objects made with pieces shaped by sawing or machining. When wood is bent, the interior face (concave) is subjected to compressive strains while the exterior face (convex) is exposed to tensile strains. Softening treatment greatly increases wood compressibility, but it has minimal effect on its tensile properties (Wangaard 1952). To restrict elongation of the convex side, it is normal to use a tension strap. Without such a restraint, the tension and compression stresses are balanced on opposite sides of a quasi-centrally located neutral axis. More- over, the addition of a steel strap with end-blocks will lead to a shift of the neutral axis of the fibers towards the convex side. As a result, the portion of the wood in tension will decrease and the one in compression will increase. A successful bending process is achieved when permanent wood deformation is achieved without obvious wood failure, either in compression or tension (Stevens and Turner 1970).

During the bending process, two kinds of deformation appear, namely plastic and viscoelastic deformations. Softening treatments (such as steaming) drive the wood into a viscoelastic state, and even after bending, the wood remains in the viscoelastic state. Inevitably, the elastic deformation results in spring-back of the wood, while the plastic deformation will remain in the desired shape (Bodig and Jayne 1982). Therefore, to avoid spring-back, the bent wood must be fixed to its position until the elastic deformation changes to plastic deformation. This change is considered as stress relaxation.

The bending of wood can be achieved through either steam, heat, or chemical treatment (Stevens and Turner 1970). In steam bending, the process variables are heat, temperature, and moisture content, while in the case of chemical treatments, ammonia is the common chemical used. Due to the ease of processing and the relatively low cost, steam bending of wood remains the most preferred method in many countries (Kollmann and Côté 1975). In steam bending, the wood pieces are placed in a steaming chamber at approximately 100 °C. The wood is then bent to the desired shape and then kept in a bending plate until cooling is completed and the final moisture content (MC) is achieved. Usually, steam bending is conducted mainly for hardwood species, which have that have initial MC values between 12% and 25%. The level of curvature and deformation achieved in the wood pieces after steam bending is often a function of its initial MC and the setting conditions (Jorgensen 1965). The suggested steaming times also vary among previous studies, although 1 hour of steaming per 25.4 mm of thickness of wood at a MC below 12%, and 30 min of steaming for similar thickness of wood at green condition is recommended (Eggert 1995). On the other hand, the maximum curvature that can be obtained when bending a given wood species of a particular thickness can be roughly estimated using the ratio of radius to thickness, known as the thickness ratio. According to Kubler (1980) this ratio should be 30 for dry wood at ambient temperature, 13 for steamed wood, and 3 when using a restraining steel strap. Despite these previous works, the underlying wood properties have been found to play an important role in determining the bending characteristics of wood species (Murakami *et al.* 2002).

Therefore, the valuation of surface smoothness and bending properties of wood from selected fast growing tree species in Malaysia, is timely and much warranted, especially when the wood harvest from the first-rotation of the fast-growing forest plantations are forthcoming. Although several studies on bending properties of wood have been published previously, reports on the bending properties of wood from forest plantation trees in Malaysia is non-existent. Ratnasingam (2021) emphasized the fact the wood bending practices in Malaysia is subjected to much trial and error, and is usually an inefficient operation, which warrants in-depth investigations. Therefore, the main objective of this study was to evaluate the surface smoothness and steam bending characteristics of *R. paulownia*, *A. mangium*, and *E. pellita*. These species were compared against rubberwood (*H. brasiliensis*), which served as the control specimen. The results of this study will provide further information on the suitability of these fast-growing wood species for furniture applications and other value-added wood products where bent components make up and contribute value to the final product.

EXPERIMENTAL

The experimental materials for this study were supplied by Sabah Forest Industries (SFI) in Sandakan, Malaysia. All the experimental planks were 25 mm × 100 mm in cross section, with a length of 1,500 mm. A total of 20 defect-free pieces of each of the four wood species (*H. brasiliensis*, *E. pellita*, *A. mangium*, and *R. paulownia*) were supplied. The wood samples had an average MC of 12 ± 2%. Upon receipt, these samples were kept in a conditioning room at a relative humidity of 65% and a temperature of 20 °C, at the Faculty of Forestry at Universiti Putra Malaysia, until the surface smoothness experiment was carried out.

Another batch of experimental materials of the four wood species were supplied for the steam bending experiment. These samples were cut to dimensions of 12 mm × 25 mm × 600 mm with a MC of 25%. A total of 90 pieces of each wood species were supplied. These samples were kept in ambient conditions until the bending experiment was carried out. The basic properties of the four wood species are shown in Table 2.

Table 2. Properties of the Four Wood Species used in this Study

Species	Density (kg/m^3) at 12% MC	Average MOE (N/mm^2)	Average MOR (N/mm^2)
H. brasiliensis	560 ± 42	15,670	98.35
E. pellita	690 ± 59	14,910	99.40
A. mangium	540 ± 38	13,262	60.95
R. paulownia	310 ± 19	5,145	47.25

*Data from supplier and MTIB (2021)

Surface Smoothness Experiment

Specimens of the four wood species, in the dimensions of 25 mm × 100 mm × 1,500 mm, with straight grain orientation were initially passed through a four-sided molder to achieve a smooth machined surface. The machining process was manipulated to achieve 25 cuts per inch or 1.0 mm pitch distance between successive cutter-marks. This is the standard industrial practice used for the evaluation of surface roughness of wood species, as reported by Ratnasingam (2021). A total of 20 planks of each species were used in this experiment. The sanding experiments was undertaken using a twin-head wide belt sander (TOP 752; Timesavers, Maple Grove, MN, USA), which had a steel contact roll in the first sanding head and a rubber contact roll (of 70A in hardness) in the second sanding head. Silicon carbide cloth-backed abrasive belts of the grit sizes 180 to 240 were used on the machine. The belt speed and feed rate were maintained at 1,000 surface m/min and 6 m/min, respectively. Other process variables such as the belt tension, specimen position and orientation, sanding pressure, and belt tracking were fixed throughout the study. The surface roughness of resultant surface was measured using the stylus method as described by Hiziroglu (1996). The values of surface roughness on the wood specimens, was expressed as maximum roughness index (R_{max}), measured in unit microns. The average roughness was determined by measuring the roughness on 10 different randomly selected spots on each of the specimen. To further analyze the surface roughness of these specimens, surface absorption tests were also carried out as described by Akbulut *et al.* (2000), which used toluene as the surface liquid. This test procedure was based on the EN 382-1 (1993) standard for the determination of surface absorption. The surface adsorption, which is closely linked to surface roughness, is measured based on the distance of spread of the toluene-drop (Ratnasingam and Scholz 2004).

Bending Experiments

All the specimens that were used in the bending experiment were straight grained and free of defects. The specimens were initially weighed and then soaked in a tub filled with water for 24 h. The next day, the weight of the wet specimens was initially recorded before steaming was carried out. The steaming of the specimens was performed in a steaming chamber (Huang Rong, Taipei City, Taiwan) for 45 min at a pressure of 0.2 bar and a temperature of 105 °C. These parameters were based on a previous study and on industrial recommendations (Sandberg and Navi 2007; Ratnasingam 2021). After steaming, each specimen was immediately weighed and inserted into a steel plate with fixed end-stops. These steel plates with the specimens were then placed in a heated bending machine (Model FC-02, Meinan Machinery, Aichi, Japan), with a curved shaped mold, which gave a radius of curvature of 10× the thickness of the specimens. The bending machine applied a pressure of 5 bar using a hydraulic press for 90 min before the pressure was released. These variables reflected current industrial practices for bent wood production (Jalaludin *et al.* 2007; Ratnasingam 2021). The steel plates that contained the bent specimens were cramped with a metal clamp to maintain a similar radius of curvature, placed in a room at 20 °C and 45% relative humidity, and conditioned for 10 days for setting and moisture conditioning.

Qualitative Assessment

For successful wood bending to be achieved, the wood must be deformed without provoking visible failures, either in tension or in compression. Thus, all the bent wood specimens were initially evaluated according to five quality grades. The grades were established according to the degree of failure in the tangential faces. Specimens without any visible signs of failure was classified as Grade 1 (excellent), while those specimens with superficial compression failures no longer than 3 mm were considered Grade 2 (good). Grade 3 (average) specimens were those with compression failures that did continue across the width of the specimen. On the other hand, specimens with compression failures that ran across the width of the specimen were classified as Grade 4 (satisfactory), and finally specimens with failure in tension were classified as Grade 5 (poor) (Fig. 1). These visual grading of bent wood were carried out in accordance with current industrial practice, as reported by Ratnasingam (2021).

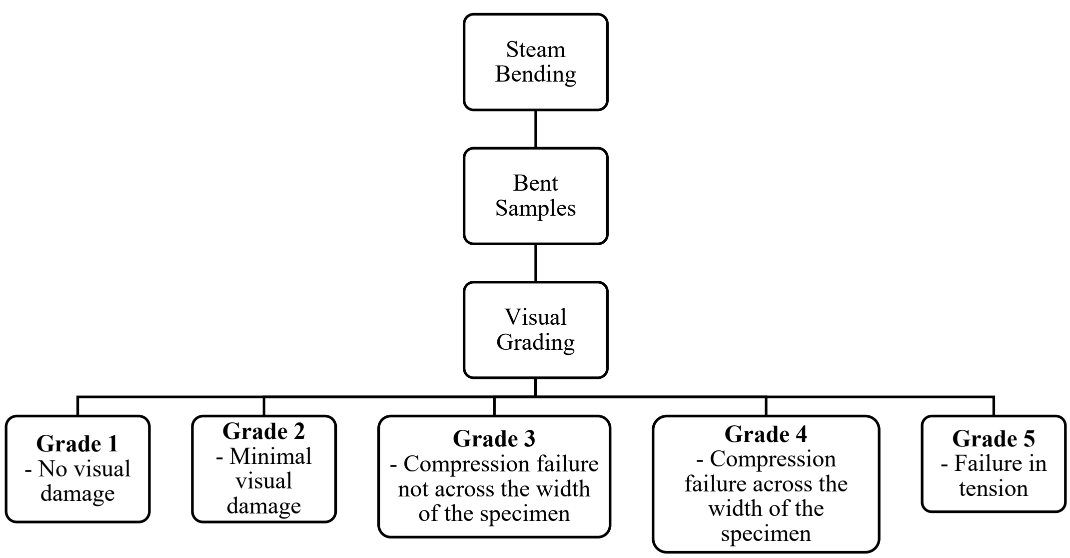

Fig. 1. Quality grading of bent wood

Quantitative Assessment

After the 10th day, the chord (C) values of the bent specimens were measured before (C_0) and immediately after removal from the cramped plate (C_{10}). The nominal chord-length of the curved-shape mold used in the bending experiment was 127.5 mm. The amount of spring-back of the specimens at day 15, 25, 35, 45, 55, and 65 were measured. This experiment allowed the memory recovery to be evaluated according to the instantaneous spring-back and the spring-back over time (Murakami *et al.* 2002). The instantaneous spring-back is the difference in chord-length between C_{10} and C_0 (both measured at day 10). The spring-back over time was the difference between the chord of the specimens measured over time (C_{15}, $C_{25}…C_{65}$) and at C_{10}. The variations in the MC of the samples were determined by monitoring the weight of the experimental samples throughout the 65 days (Fig. 2).

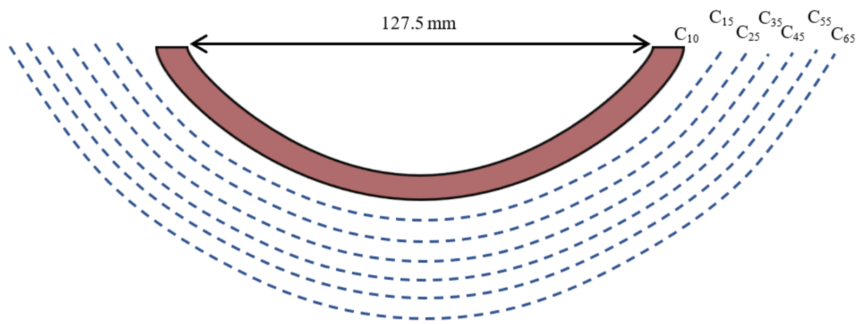

Fig. 2. Spring-back measurement in bent sample

All data from this study were subjected to statistical tests. The significant differences between the surface smoothness, quality of bending, and extent of spring back of the four wood species were evaluated using the analysis of variance (ANOVA) tests. The statistical analysis was carried out using the SPSS version 10.1 statistical analysis software (IBM, Armonk, NY, USA), and the significance level was set at $p < 0.05$.

RESULTS AND DISCUSSION

Comparative Surface Roughness of the Different Wood Species

Generally, a good wood surface quality is achieved when using straight-grained wood specimens. In this respect, the wood sanding operation as an orthogonal cutting process was done to ensure that sanding of the specimens was carried out in the direction parallel to the grain (Ratnasingam and Scholz 2004). Table 3 shows the surface roughness (R_{max}) based on the stylus measurements of the four wood species. It was clear that *H. brasiliensis* and *E. pellita* specimens produced the significantly better surface smoothness compared to the *A. mangium* and *R. paulownia* specimens. However, no significant difference in the surface roughness was observed between the rubber *H. brasiliensis* wood and the *E. pellita* specimens, while a significant difference was observed between the surface roughness of the *A. mangium* and *R. paulownia* specimens. The observed differences in the resultant surface roughness of these specimens can be attributed to its different anatomical features, which determines the sizes of the cellular elements. This results in the inherent surface roughness of the wood species (Bendtsen 1978).

As has been reported previously by Akbulut *et al.* (2000), there is a direct relationship between the wood surface smoothness and surface absorption. To verify the surface roughness data obtained through the stylus measurements as above, a series of surface absorption tests were conducted on the specimens of the four wood species. The results obtained from these tests also confirmed findings obtained from the earlier part of this study. As shown in Table 3, the *H. brasiliensis* samples showed the least surface roughness, followed by the *E. pellita* specimens, the *A. mangium* specimens, and finally the *R. paulownia* specimens, which was based on the distance of the toluene drop spread over the surface of the respective specimens. This can be explained by the increased tendency of the toluene to be captured by capillary forces arising from greater surface area exposed on the rough wood surface (Akbulut *et al.* 2000; Ratnasingam and Scholz 2004).

Table 3. Surface Roughness Properties of the Four Wood Species

Species	R_{max} Value	Distance of Toluene Spread (mm)
H. brasiliensis	68.1 ± (3.3)	143 ± (2)
E. pellita	69.3 ± (5.1)	144 ± (3)
A. mangium	81.4 ± (6.8)	193 ± (5)
R. paulownia	86.9 ± (4.4)	217 ± (9)

*Standard error in parentheses

Qualitative Assessment of the Comparative Bending Quality

The qualitative analysis of the bent specimens from all four wood species showed that the *R. paulownia* wood specimens had 12% defect-free bent specimens (Grade 1), while the other three wood species had none. For the Grade 2 specimens, the *H. brasiliensis*, *E. pellita*, *A. mangium*, and *R. paulownia* had defect-free proportions of 72%, 39%, 31%, and 54%, respectively. Table 4 shows the number of specimens of each wood species that fell into grades 1 to 5. It must be noted that failures in bent specimens occur when the steamed specimens are stressed beyond their inherent tensile or compressive strength limits. Compressive failures are often due to high stress, defects, or zones of weakness in the specimens (Murakami *et al.* 2002). On the other hand, tensile failures occur when sufficient pressure has not been applied on the specimens to keep the tension side of the specimens below the limit of 2% of the specimen length (Stevens and Turner 1970).

A further analysis as described in Ozarska and Daian (2010) was applied to find the probability of obtaining wood specimens with good bending quality. According to this approach, it is appropriate to use a 95% confidence level to indicate the safe level at which wood specimens may be bent, to an extent on that 5% of the total bent specimens will fail or fall into Grade 5 during the bending process. In this approach, the frequency distribution of the visual ranking of the bent specimens of all the wood species were first presented as percentage of specimens in the different ranking groups (Table 4).

Table 4. Frequency Distribution by Visual Ranking

Species	Visual Ranking (%)					No. of Samples
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
H. brasiliensis	-	69	18	8	5	90
E. pellita	-	39	27	24	10	90
A. mangium	-	31	27	33	9	90
R. paulownia	12	14	29	32	13	90

The cumulative frequency distribution was used to establish the minimum level at which the bent specimens of each wood species fail at a 95 % confidence level (Table 5). Based on the results, it is apparent that only rubberwood met the just satisfactory criterion. This means that at least 95% of the rubberwood specimens passed the qualitative criteria as required at this level (1+2+3+4+5). The other wood species, *E. pellita*, *A. mangium*, and *R. paulownia* did not meet this threshold, and they were rated as woods with poor bending quality.

Table 5. Cumulative Frequency Distribution by Visual Ranking

Species	Cumulative Frequency Distribution by Visual Ranking				
	Excellent 1	Good 1+2	Average 1+2+3	Satisfactory 1+2+3+4	Poor 1+2+3+4+5
H. brasiliensis	0	69	87	95	100
E. pellita	0	39	66	90	100
A. mangium	0	31	58	91	100
R. paulownia	12	26	55	87	100

Despite the fact that the *R. paulownia* wood species had a few pieces classified as Grade 1, it did not meet the overall criteria to be classified as a wood species with satisfactory bending quality. As reported previously, the bending quality of a wood species is not only dependent on its density, but also dependent on its anatomical structure and its strength characteristics (Murakami *et al.* 2002; Rice and Lucas 2003). As shown in Table 2, the 4 experimental species used in this study have markedly different properties. It must be emphasized that the medium density and evenly textured rubberwood gives the best bending performance compared to the other wood species. The presence of strength reducing characteristics such as juvenile wood, cracks, twists, and knots can also impair the bending property of wood, as experienced in the case of *A. mangium* and *R. paulownia*. In this context, the poor performance of the *E. pellita* and *A. mangium* specimens in terms of their bending quality may also be explained by the presence of weakness zones in the samples, due to improper grain directions and a proportion of abnormal wood (Kang 2010).

Quantitative Assessment of the Bending Quality of the Different Wood Species

Instantaneous spring-back

The instantaneous spring-back of the different wood species measured at day 10 was an average of 11.2 mm. The *H. brasiliensis* had the least spring-back, while the *R. paulownia* had the highest spring-back (Table 6). The statistical test showed that the density of the wood species had a significant influence on the instantaneous spring-back observed, and it is apparent that wood with a higher density has higher spring-back compared to wood with a lower density (Murakami *et al.* 2002).

Table 6. Means of Instantaneous Spring-Back for the Four Wood Species

Species	Instantaneous Spring-Back (mm)
H. brasiliensis	6.3 (0.4)
E. pellita	8.9 (1.2)
A. mangium	10.4 (0.9)
R. paulownia	12.3 (0.7)

*Standard error in parentheses

One interesting point observed from this study is that the instantaneous spring-back values were affected by the loss of moisture from the specimens during the setting period. It was found that the average MC of the specimens had decreased from 14.1% immediately after steaming down to 12.4% at day 10. This decrease in the MC negatively affected the instantaneous spring-back. The samples with the higher MC decrease showed lower values of instantaneous spring-back, and vice-versa. According to Lemoine and Koch (1971) and Murakami *et al*. (2002), wood pieces that gain moisture by steaming usually became more plastic and had a lower recovery effect. Inevitably, this finding suggests that a higher initial MC, or a much longer steaming period is highly desirable to improve the bending performance of wood. Furthermore, as reported by Bodig and Jayne (1982), the rigidity of wood tends to increase as the wood MC decreases. The instantaneous spring-back observed in bent wood is essentially the release of the compressive force imposed during the bending process. To reduce this effect, the bent wood is held in position in a clamp until it sets and dries (Peck 1957; Stevens and Turner 1970). Based on the results of this study, it may also be suggested that a much longer setting period could have been used to minimize instantaneous spring-back, as suggested by Jalaludin *et al.* (2007), who found that bent wood's spring-back is reduced when it is allowed to set for a long period until it reaches the desired equilibrium moisture content (EMC) level. The steadily reducing MC of the specimens from day 10 to day 65 also suggest that the final EMC was not reached by the specimens, and a much longer setting time would be desirable to reduce the instantaneous spring-back.

Spring-back over time

It is apparent that the EMC of the bent specimens was not reached after 10 days, and the spring-back measurements were continued until day 65 under the same conditions. Between days 10 and 65, the bent specimens showed further spring-back, and the average spring-back was found to be 13.2 mm (Fig. 3). On the other hand, the MC of the specimens averaged from 12.4% at day 10 to 11.3% at day 65 (Fig. 4). Bent pieces sprang-back further during this period. The average spring-back over time was 10.9 mm. The statistical test showed that this small reduction in the MC appears to have a significant effect on the spring-back of the specimens. One point that is worth highlighting is the fact that specimens with a smaller reduction in the MC recorded lower spring-back, compared to specimens with a higher reduction in the MC.

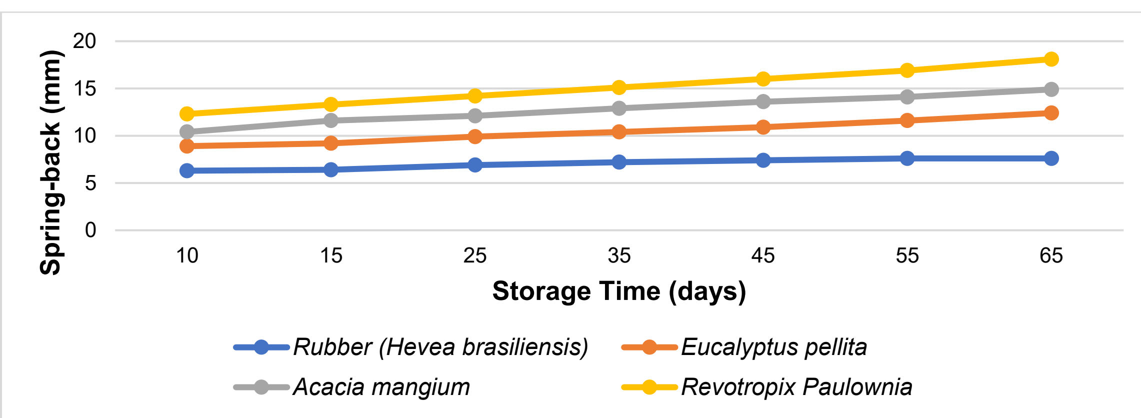

Fig. 3. Spring-back over time of the four wood species

Interestingly, the variation in the MC of the specimens had a significant effect on the spring-back over time. This finding is similar to an earlier report by Rice and Lucas (2003), which found that the MC of bent wood specimens must be stable to minimize the amount of spring-back. The MC had a linear relationship on the spring-back effect observed, especially in specimens that were less than 12 mm thick.

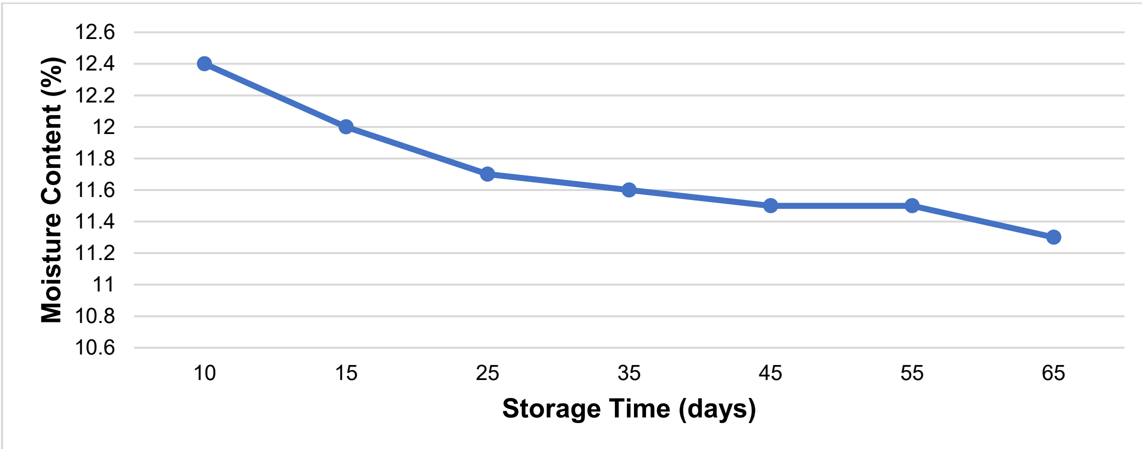

Fig. 4. Average MC variations in the four wood species over time

Previous studies have found that clones and the site of planting, which influenced the basic wood properties, had a pronounced effect on the bending quality of wood (Murakami *et al.* 2002; Ayarkwa *et al.* 2011; Ratnasingam 2021). Furthermore, the drying treatment, steaming period, initial MC, the length of bent specimen setting, and the length of the conditioning period also affected the overall bending quality, apart from the resulting spring-back in the bent specimens (Stevens and Turner 1970). Bendtsen (1978), Eggert (1995), and Ratnasingam (2021), implied that not all wood species are suitable for bending, and the anatomical and strength properties are the main determinants that affect the bending quality of a particular wood species. As shown in this study, the sample with the lowest density, *R. paulownia*, appeared to have the poorest bending performance. On the other hand, while the *E. pellita* and *A. mangium* were higher in density, they had lower bending performance compared to the *H. brasiliensis*. The tendency to split in the *E. pellita* and *A. mangium* wood was attributed to the pitted fibers and other cellular elements, especially upon drying and bending. This may explain the lower bending performance of these species compared to *H. brasiliensis*. Furthermore, *E. pellita*, *A. mangium*, and *R. paulownia* have a relatively higher proportion of abnormal wood, and less straight grains compared to *H. brasiliensis* (Gan *et al.* 2011; Ratnasingam *et al.* 2020; Japarudin *et al.* 2021).

Industrial Implications

Steam bending properties are highly desirable for wood materials that are used for furniture applications (Jorgensen 1965). The results from this study confirm that *H. brasiliensis* wood has the best bending performance among the four species of wood from fast-growing forest plantation species. Stevens and Turner (1970) and Benson (2009) suggested that wood species with a density of at least 500 kg/m^3 appear to bend better than woods with a density of less than 400 kg/m^3. In the case of the *R. paulownia* wood, with its accelerated growth rates, the wood has a substantial amount of tension wood in its higher proportion of juvenile wood. Furthermore, the density of 300 kg/m^3 makes *R. paulownia* wood unsuitable for bending purposes. Tension wood has been shown to have poor surface and machining qualities (Gan *et al.* 2011), in addition to its lower strength properties and its higher tendency prone to collapse. A similar point is also relevant to *E. pellita* and *A. mangium* woods. The higher proportion of tension wood in these species negatively impacts their bending properties. Furthermore, as higher initial MCs appear to improve the overall bending performance, it may be implied that the 25% MC of the specimens used for steam bending may be too low, and a higher MC is better. In fact, as reported by Bodig and Jayne (1982), wood plasticity increases with temperature and MC. Therefore, a longer steaming period is highly desirable for improving the bending performance. Against this background, it may be suggested that more research is needed to obtain optimum steaming, drying, and setting conditions for steam bending of tropical wood.

Based on the results from this study, it is apparent that *H. brasiliensis* has the best bending properties, followed by *A. mangium*, *E. pellita*, and finally *R. paulownia*. In this context, the preference for *H. brasiliensis* as the leading furniture making material in Malaysia is further justified through this study. More research however, needs to be carried out to improve the overall acceptance of *E. pellita*, *A. mangium*, and *R. paulownia* as furniture materials, although their strength properties may favor such applications.

The results from this study also add much required information on the woodworking properties of the plantation forest trees, which are being aggressively cultivated in the country. As emphasized by Ratnasingam *et al.* (2018) and Ratnasingam (2021), the success of new wood materials from plantation forests is often compared that of rubberwood, which has long established itself as the primary wood raw material for the large wood-based industry in the country.

CONCLUSIONS

1. This study showed that the *H. brasiliensis* wood has the best steam bending performance, followed by *E. pellita*, *A. mangium*, and finally *R. paulownia*.
2. The instantaneous and spring-back over time of the four wood species also followed a similar trend.
3. The study showed that the MC played an important role in determining the steam bending performance of wood.
4. The study also shows that the *E. pellita* and *A. mangium* wood, despite having acceptable densities, still recorded inferior steam bending performance compared to the *H. brasiliensis*, which may be attributed to its anatomical characteristics.
5. The study also reveals that *H. brasiliensis* has the least surface roughness compared to the other wood species, clearly highlighting its wide acceptance as a furniture material.
6. The study also confirmed that *R. paulownia* may not be suitable for load-bearing applications due to its low density and poor bending performance.
7. Further studies on steam bending of these four wood species should be carried out to optimize the process variables used, and to improve its overall efficiency.

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