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Investigation of Drying Characteristics and Appropriate Drying Conditions of Three Acacia Wood Species

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Contents

List of Tables

List of Figures

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Abstract

In this research, the drying characteristics and appropriate drying conditions of three Acacia wood species, *Acacia mangium* Willd., *Acacia crassicarpa* A. Cunn. ex Benth. and *Acacia aulacocarpa* A. Cunn. ex Benth., were investigated. These species were collected from Tarpathon Research Station No. 9 in Mudon Township, Mon State. One 26-year-old tree was collected for each species. Wood specimens were prepared by cutting parallel to the growth rings from the heartwood portion free from defects, knots, and decay. The Quick Drying Test method of Terazawa (1965) modified by Jonkosky (1992) was used to investigate the drying characteristics, and appropriate drying conditions were formulated based on these drying characteristics. The results showed that all three acacia species exhibited small initial checks (end checks and surface checks) (Class 3) during the initial drying stage. *Acacia mangium* had severe deformations (Class 7), while *Acacia crassicarpa* and *Acacia aulacocarpa* had slight deformations (Class 2). *Acacia crassicarpa* did not show any internal checks or honeycombing (Class 1), but *Acacia mangium* had severe honeycombing (Class 5) and *Acacia aulacocarpa* had moderate honeycombing (Class 3). The initial moisture contents of *Acacia mangium*, *Acacia aulacocarpa*, and *Acacia crassicarpa* were 96.12%, 95.47%, and 92.63%, respectively. Based on these results, in the kiln drying of 25 mm thick lumber to get below 10% moisture content, *Acacia mangium* lumber should be dried in a drying condition with a temperature of 50-75°C and a relative humidity of 85% - 20%. *Acacia aulacocarpa* lumber should be dried at a temperature range of 55-80°C, and a relative humidity of 81%-22%. Similarly, *Acacia crassicarpa* lumber should be dried at a temperature range of 55-80°C and a relative humidity of 81% to 22% to prevent drying defects.

Keywords: *initial check, deformation, honeycombing, temperature, relative humidity, moisture content, quick drying test, three Acacia species*

Acacia သစ်မျိုးစိတ်သုံးမျိုး၏ အခြောက်ခံမှုစရိုက်လက္ခဏာများနှင့် သင့်လျော်သော အခြောက်ခံမှုအခြေအနေများအား လေ့လာဖော်ထုတ်ခြင်း

စုစုလှိုင်၊ လက်ထောက်သုတေသနအရာရှိ
သစ်တောသုတေသနဌာနခွဲ

စာတမ်းအကျဉ်း

ဤသုတေသနစာတမ်းတွင် Acaciaသစ်မျိုးစိတ်သုံးမျိုးဖြစ်သော*Acacia mangium* Willd., *Acacia crassicarpa* A.Cunn. ex Benth. နှင့် *Acacia aulacocarpa* A.Cunn. ex Benth. တို့၏ အခြောက်ခံမှုစရိုက်လက္ခဏာများနှင့် ယင်းသစ်မျိုးများနှင့် သင့်လျော်သော အခြောက်ခံမှု အခြေအနေများကို စမ်းသပ်လေ့လာ တင်ပြထားပါသည်။ ဤသစ်မျိုးစိတ်များကို မွန်ပြည် နယ်၊ မုဒုံမြို့နယ်ရှိ တာပသွန်သုတေသနစခန်းအမှတ်(၉)မှ မျိုးစိတ်တစ်မျိုးစီ အတွက် သက်တမ်း ၂၆နှစ်သားရှိ သစ်နမူနာပင် တစ်ပင်စီစုဆောင်းခဲ့ပါသည်။ သစ်နမူနာများကို အမျက်များနှင့် အပြစ် အနာအဆာများလွတ်ကင်းသည့် အနှစ်သားပိုင်းများမှ နှစ်ကွင်းနှင့် အပြိုင် ခွဲစိပ်ပြင်ဆင် ခဲ့ပါသည်။ Jonkosky (1992) မှ ပြုပြင်ထားသော Terazawa (1965) ၏ Quick Drying Test နည်း စနစ်ကို အသုံးပြု၍ အခြောက်ခံမှုစရိုက်လက္ခဏာများ စမ်းသပ်လေ့လာခဲ့ပြီး အဆိုပါ လက္ခဏာ များကိုအခြေခံ၍ သင့်လျော်သော အခြောက်ခံမှုအခြေအနေများကိုဖော်ထုတ်ခဲ့ပါသည်။ စမ်းသပ် မှုရလဒ်များအရ Acacia သစ်မျိုးစိတ်သုံးမျိုးသည် ကနဦး အခြောက်ခံသည့် အဆင့်တွင် ကနဦး အက်ကွဲမှုများ (ထိပ်အက်ခြင်းနှင့်မျက်နှာပြင်အက်ခြင်း) (အဆင့် ၃) ဖြစ်ပေါ်ခဲ့ပါသည်။ *Acacia mangium* သည် ပြင်းထန်သောပုံပျက်ခြင်း (အဆင့် ၇) ရှိခဲ့ပြီး *Acacia crassicarpa* နှင့် *Acacia aulacocarpa* တို့သည် အနည်းငယ်ပုံပျက်ခြင်း (အဆင့် ၂)ရှိခဲ့ပါသည်။ *Acacia crassicarpa* သည် ပျားအုံသဏ္ဍာန် ကွဲအက်ခြင်းများ (အဆင့် ၁) မရှိခဲ့သော်လည်း *Acacia mangium* သည် ပြင်းထန် သော ပျားအုံသဏ္ဍာန် ကွဲအက်ခြင်းများ (အဆင့် ၅)ရှိခဲ့ပြီး *Acacia aulacocarpa* သည် အလယ် အလတ်ဖြစ်သော ပျားအုံ သဏ္ဍာန် ကွဲအက်ခြင်းများ (အဆင့် ၃) ရှိခဲ့ပါသည်။ *Acacia mangium*၊ *Acacia aulacocarpa* နှင့် *Acacia crassicarpa* တို့၏ အစိုဓာတ်ပါဝင်မှုပမာဏများမှာ ၉၆.၁၂ ရာခိုင်နှုန်း, ၉၅.၄၇ ရာခိုင်နှုန်းနှင့် ၉၂.၆၃ ရာခိုင်နှုန်း အသီးသီးဖြစ်ပါသည်။ အဆိုပါ ရလဒ်များ အပေါ်အခြေခံ၍ ၂၅ မီလီမီတာ (၁ လက်မ) ထု ရှိသော သစ်ခွဲသားများအား အစိုဓါတ် ပမာဏ ၁၀ ရာခိုင်နှုန်း အောက်ရရှိရန် ပေါင်းဖိုဖြင့် အခြောက်ခံရာတွင် အခြောက်ခံမှုဆိုင်ရာ အပြစ် အနာ အဆာ များမှကာကွယ်ရန် *Acacia mangium* သစ်ခွဲသားများအား အပူချိန် ၅၀-၇၅ ဒီဂရီ စင်တီ ဂရိတ်၊ စိုထိုင်းဆ ၈၅-၂၀ ရာခိုင်နှုန်း ဖြင့်လည်းကောင်း၊ *A. aulacocarpa* နှင့် *A. crassicarpa* သစ်ခွဲသားများအတွက် အပူချိန် ၅၅-၈၀ ဒီဂရီစင်တီဂရိတ်၊ စိုထိုင်းဆ ၈၁-၂၂ ရာခိုင်နှုန်းရှိသော အခြောက်ခံမှု အခြေအနေများတွင် အခြောက်ခံသင့်ပါကြောင်း အကြံပြုတင်ပြထားပါသည်။

Investigation of Drying Characteristics and Appropriate Drying Conditions of Three Acacia Wood Species

1. Introduction

Acacia, a fast-growing tree species, belongs to the genus Acacia in the family Fabaceae. According to Plants of the World Online (2024), there are 1,085 species of shrubs and woody trees native to regions such as Australia, New Guinea, Southeast Asia, Hawaii, and the Mascarene Islands. Many of these species have also been introduced to other parts of the world, including Myanmar. Acacia wood is known for its strength, attractive grain patterns, and various colors ranging from light yellow to dark brown. It is used in various applications, including attractive furniture, cabinet making, flooring, interior decoration, tool handles, pulp and paper, veneer, plywood, joinery, and boat building in Australia and other countries (Lim 2003). Although Acacia wood is valued in the global market, it is not yet widely used in Myanmar because Myanmar people prefer native wood species such as Teak and Padauk for furniture and utensils, and Pyinkado and In-Kanyin for construction purposes.

In Myanmar, the wood and wood products industry relies heavily on the country's natural forests, which are abundant in valuable native wood species. These forests support important sectors such as housing, construction, and furniture manufacturing. However, valuable native wood species are becoming increasingly scarce due to overexploitation and environmental pressures, leading to a rise in timber prices. Nowadays, Acacia trees are being planted in research plantations for seed orchards and seed production, and commercial plantations and community forests are being established to support sustainable resources and reduce deforestation. These plantations include the species *Acacia mangium* Willd., *Acacia crassicarpa* A.Cunn. ex Benth., and *Acacia aulacocarpa* A.Cunn. ex Benth.

As plantation establishment efforts continue, it is expected that the availability of acacia wood for industrial use will increase. As native timber species decline, understanding the wood characteristics of these plantations becomes increasingly important in providing high-quality timber for the wood processing sectors. Enhancing the quality of acacia wood through better processing techniques will increase its value, support the domestic market, and expand international trade.

Wood drying is one of the most important and fundamental processes in wood processing. It affects wood quality, dimensional stability, workability, susceptibility to insect attack, and the aesthetics of wood used in high-value-added products. However, not all wood species are easy to dry, especially in a kiln, without developing any defects such as checking, honeycombing, warping, cracking, and collapse, which reduce the grade and value of lumber and the final product. These drying defects can be caused by various factors, including density, species, age, drying method, sapwood and heartwood, sawing pattern, position within the tree, board thickness, initial moisture content, and drying schedule. Drying the wood with as few defects as possible is the main objective in the drying process (Rahimi et al., 2011).

Drying condition is a series of combinations of temperature and relative humidity, called a drying schedule, and is important in controlling the drying process for each wood species. Proper control of drying conditions prevents drying defects and contributes to the overall success of the drying process. The correct temperature helps the evaporation of moisture from the wood, while an appropriate humidity level prevents the wood from drying too rapidly and developing defects. According to Effah (2014), it is important to note that each wood species has its own unique drying characteristics and different sensitivity to drying temperature. Understanding the drying characteristics of each wood species is essential in determining the appropriate drying conditions for that wood species. Appropriate drying conditions not only reduce energy consumption, drying time, costs, and drying defects, but also increase the drying rates and improve the quality of wood.

Therefore, there is a need for information about drying characteristics and conditions that are important for the effective utilization of Acacia wood. Since these woods have not been used commercially in the past, their drying conditions are not yet developed, and their sensitivity to drying characteristics is unknown. This information will help improve processing techniques, enhance wood quality, and promote the sustainable use of Acacia wood as a raw material for various industrial applications in Myanmar.

2. Objectives

The objectives of this study are:

(1) to investigate the drying characteristics of *Acacia mangium, Acacia crassicarpa* and *Acacia aulacocarpa*,

(2) to formulate the appropriate drying conditions based on these drying characteristics, and

(3) to enhance the efficiency of the drying process by using these drying conditions.

3. Literature Reviews

Acacia crassicarpa A. Cunn. ex Benth. wood is native to Queensland, Australia and New Guinea. It is strong and durable and has many uses, such as for a wide range of uses, including light structural and decorative applications such as construction, furniture, flooring, boards, and boat building. The sapwood is pale yellowish-brown, and the heartwood is golden-brown (Orwa et al. 2009).

Acacia aulacocarpa A. Cunn. ex Benth. is native to southern Papua New Guinea, eastern Queensland, and New South Wales. It is recommended to have an 8-10-year rotation for pulpwood plantations and a 15-20-year rotation for saw logs. The sapwood is narrow and has a creamy yellow to straw-colored appearance, making it distinct from the olive-brown to grey-brown or reddish-brown heartwood. The wood is known for its hardness and heaviness, and has moderate toughness and durability. It is commonly used in construction timber, as well as for attractive furniture and cabinetwork, flooring, boat building, tool handles, boxes and crates, door and window frames, joinery, and turnery (Orwa et al. 2009).

Acacia mangium Willd. is native to northeastern Queensland in Australia, Indonesia, Western Papua New Guinea, and it is commonly known as mangium. It is recommended to have a 6-7 year rotation for pulpwood plantations and a 15-20-year rotation for sawn timber (Orwa et al. 2009). This wood has a wide range of uses, including attractive furniture and cabinetmaking, door frames, window parts, light to heavy construction, moldings, poles, posts, paneling, mining timbers, boat building, carts, joinery, turnery, tool handles, agricultural implements, splints, particle boards, hardboard, and veneer, as well as for plywood, pulp, and paper (Orwa et al. 2009). The sapwood is typically white or yellowish-white, while the heartwood has a fresh yellowish-brown to golden-brown colour, which fades to a dull brown overtime. Due to its strong mechanical properties, it is often used as a structural material (Arisman & Hardiyanto 2006). The timber can be kiln-dried well and fairly rapidly without serious defects (Wong 2002).

The Quick Drying Test was originally designed and developed by Terazawa (1965, 1976) at the Forestry and Forest Products Research Institute of Japan. It has become widely known as a simple and effective method for predicting wood-drying characteristics and determining an appropriate drying schedule, including temperature and relative humidity, for any timber species. This initial schedule was then modified using “The Optimum Schedule

Test" until an acceptable schedule was found. In their paper, Terazawa and his team tested thirty-seven wood species from Japan using this method and provided the initial kiln drying schedules for each species, based on the American method or the Madison Forest Products Laboratory standard.

In 1983, the Wood Drying Working Party recommended the development of drying schedules to improve the quality of drying, particularly in tropical regions where there are variations in species (Vermaas, 1983 as cited in Jankowsky, 1992 and Simpson, 1992), . Hisada et al. (1986) from Forestry and Forest Products Research Institute of Japan (FFPRI) conducted a Quick Drying Test on 60 tropical timber species. By analyzing the different drying defects that occurred during the tests, they were able to estimate initial drying schedules for each species. Based on these findings, charts were created to estimate patternized kiln drying schedule codes, with 25 patterns of dry bulb temperature and wet bulb depression. These charts were used to identify the most appropriate patternized schedules from the preliminary results and standardized patternized drying schedules were then established for each timber species in their research.

In 1998, Sumi et al. conducted a study on the kiln drying properties of nine species of Sarawak Timbers. They used the "Quick Drying Test" method and utilized charts developed by Hisada et al. (1986). The results of the drying test were used to develop suitable kiln drying schedules for 25 mm (1-inch) thick lumber, as outlined in their paper. The author reported that, the patternized schedules developed by Hisada et al. (1986) from FFPRI cover more than 90% of drying schedules for Southeast Asian species and are more refined than the schedules derived from the American method, which is based on 14 patterns of dry bulb temperature and 8 patterns of wet bulb depression (Torgeson 1951), and the British method, which is based on 12 drying patterns (Stevens 1952). These two methods are based on the drying schedules of species grown in temperate zones and are difficult to apply to the drying of tropical species.

In 1999, Aung Kyaw and Win Kyi conducted a study titled "Proposed kiln schedules for thirty lesser-used timber species of Myanmar". The study utilized the "Quick Drying Test" and referenced schedules tables developed by Hisada et al. (1986). The researchers categorized the thirty species into four groups based on their drying defects: non-refractory timbers, moderately refractory timbers, refractory timbers, and very refractory timbers. They also stated that further kiln drying tests could be conducted to determine the "Optimum Kiln Schedules" for these species, based on the findings presented in their study.

Soe et al. (2013) also investigated the proposed kiln schedule of some commercial hardwood species from Tanintharyi Region, based on the "quick drying test" and using patternized schedule tables developed by Hisada et al. (1986). The tested species were categorized into four classes including non-refractory, moderately refractory, refractory, and very refractory timbers, based on the drying defects.

In 2010, Gan et al. conducted a study on the drying of *acacia mangium* using a conventional kiln drying system. The author used two drying conditions with low temperature of 48°C and 45°C and initial relative humidity of 88% and 86% for drying 16-year-old boards with a thickness of 30 mm that were sourced from Ulu Sedili, Johore, and Kemasul, Pahang, located in Peninsular Malaysia. These schedules were based on the "Quick Dry Test" which utilizes the dry bulb temperature and wet bulb depression from the Madison Table in the Forest Products Laboratory Manual. The initial schedules were then modified by using "The Drying Schedule Test." They observed that reducing the initial dry bulb temperature and increasing humidity did not result in satisfactory drying due to the occurrence of wet core. It was also found that air-drying the boards before kiln-drying reduced the formation of wet cores.

In 2014, Tan developed dry kiln schedules for *Acacia mangium* wood of different ages (7, 10, and 13 years) using the Madison schedule table. He suggested that specific drying conditions for each age group: a 7-year-old, an initial dry bulb temperature of 42°C with 90% relative humidity and a final temperature of 65°C with 90% relative humidity; for a 10-year-old, an initial dry bulb temperature of 47°C with 86% relative humidity and a final temperature of 70°C with 35% relative humidity; and for a 13-year-old, an initial dry bulb temperature of 48°C with 88% relative humidity and a final temperature of 73°C with 52% relative humidity.

In 2015, Basri et al. conducted a study on the basic properties and drying quality of 9-year-old *Acacia mangium* wood from a plantation of the Forest Research and Development Agency in Bogor, Indonesia. The purpose of the study was to evaluate the effects of girdling periods (0, 4, and 8 months) applied before cutting the trees. The author indicated that a long girdling period led to improved quality of dried lumber. Additionally, they recommended a drying schedule with a temperature range of 50–80°C and relative humidity between 80% and 28%.

4. Materials and Methods

4.1. Materials

4.1.1. Sample Collection, Preparation, and Equipment

Three Acacia species, *Acacia mangium* Willd, *Acacia crassicarpa* A.Cunn. ex Benth., and *Acacia aulacocarpa* Cunn. ex Benth., were studied in this research. These species were 26 years old and collected from a research plantation established by the Forest Research Institute in 1998. This plantation was established as a seedling seed orchard and seed production area at Tarpathon Research Station No. 9 in Mudon Township, Mon State. One sample tree was collected for each species. The measurements at breast height were *Acacia crassicarpa* with a girth of 99.06 cm (3 feet 3 inches), *Acacia aulacocarpa* with a girth of 83.82 cm (2 feet 9 inches), and *Acacia mangium* with a girth of 81.28 cm (2 feet 8 inches).

Each tree was cut into 1.83 m (6-ft) parts and the lumbers were cut in a tangential direction and flat-sawn boards were taken from the heartwood. These boards were then cut into sizes of 20 mm (thickness) by 100 mm (width) by 200 mm (length). All specimens were carefully selected to be free from defects such as knots and decay. After that, sawdust adhering to the boards were removed and labeled on the surface of wood specimens. Next, the specimens were maintained in a green condition before running the test by fully immersing them in water.

The experiments were conducted at the wood drying laboratory of the Forest Research Institute. Each experiment was performed three times to get the best results. The equipment used included a laboratory oven, an electric balance, and a digital caliper.

4.2. Method

4.2.1. Evaluation of drying characteristics or defects

The Quick Drying Test method was used to determine the drying characteristics. This method originally developed by Terazawa (1965) and later modified by Jankowski (1992) and Hisada et.al. (1986), was used in this research.

Before testing, each specimen was weighed using a digital balance, and the initial green weight was recorded for moisture content calculation, and then dried in an oven at a temperature of 103 ± 2°C. During the first eight hours of drying, the test specimens were weighed. At the same time, initial checks, including surface and end checks were evaluated, measured, and carefully recorded at one-hour intervals. This process was repeated until the wood specimens reached a constant weight.

After getting the constant weight, the final weights of all wood specimens were recorded. The moisture content of each sample was calculated according to the standard formula based on the oven-dry weight. Next, each specimen was then cut in half again to evaluate the honeycomb shape and measure deformation. Using a digital caliper, measurements were taken at the thickest point (A) and the thinnest point (B) along the four edges of each half. The differences between these measurements (A - B) were then calculated for each of the four positions to determine the deformation. At the same time, the number of honeycombs and their sizes on newly surfaces were also carefully examined and counted.

4.2.2. Data collection and analysis

The data collected were initial moisture contents, measurements and numbers of drying defects that include initial checks (surface checks, end checks, and end-to-surface checks), internal checks (honeycombing), and deformation. Severe defects were evaluated using Terazawa's method, and the wood specimens were assigned a grade based on the classification outlined in Tables 1 and 2. A higher grade indicates a more severe defect, and a lower grade indicates a less severe defect. The highest grade from each specimen was used to determine the initial and final temperature, wet-bulb depression, and relative humidity.

Table1. Classification of initial checks and honeycombing based on Terazawa (1965) and modified by Jankowski (1992)

Class no.	Initial Checks - D_1		Honeycombg (internal checks) - D_3
	End check (mm)	Surface check (mm)	
1	No check	No check	No check
2	Small checks L<10 W< 0.8	Small checks L<50 W<0.5	Large 1, Small 2
3	Small checks L >10 W< 0.8	Small to medium checks 5<L<100 1<W<10	Large 2, Small 4-5 Large 1 & small 3
4	Medium checks L<10 0.8<W<1.5	Medium to large checks L<150 W<1.5	Large 4, Small 7-9 Large 1 & small 4-6
5	Medium to large checks L>10 0.8<W<1.5	Large checks L >150 W>1.5	Large 6-8, Small 15 Large 4 & small 6-8
6	Large checks L >10 L >150	Large checks L >150 W>1.5	Large15-17, small checks appearing continuously

Note: L = check length, W= check width

Source: Jankowski (1992), Terazawa (1965)

Table 2. Classification of deformation – D_2

Deformation	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
A-B (mm)	0~0.3	0.3~0.5	0.5~0.8	0.8~1.2	1.2~1.8	1.8~2.5	2.5~3.5	> 3.5

Source: Terazawa (1965)

4.2.3. Formulation of drying conditions

Based on the drying characteristics and initial moisture content, the code numbers of patternized Dry-Bulb Temperature (DBT) and Wet-Bulb Depression (WBD) schedules for *Acacia mangium, Acacia crassicarpa* and *Acacia aulacocarpa* were determined using the charts developed by Hisada et al. (1986) as shown in Figures 1 and 2.

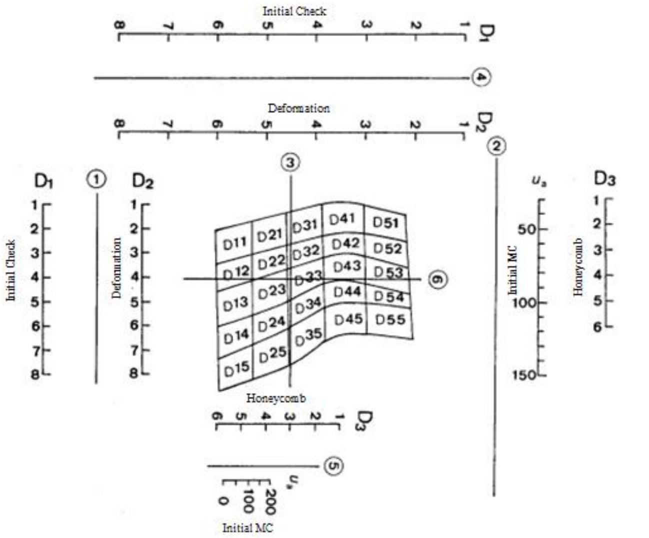

Figure 1. Chart for the code number of patternized dry-bulb temperature schedule (based on Hisada et al. 1986)

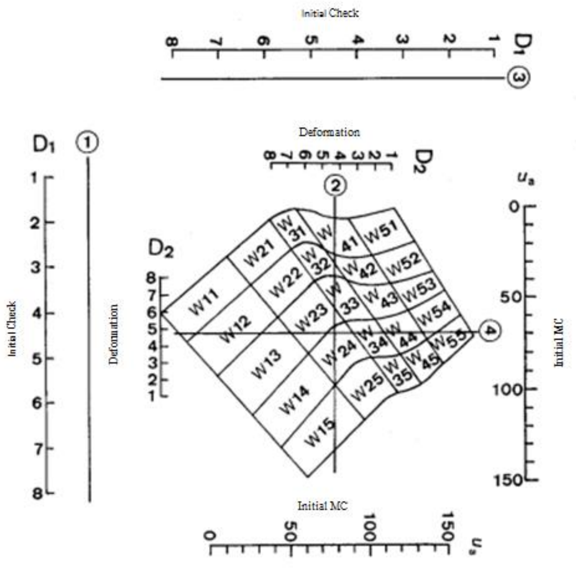

Figure 2. Chart for the code number of patternized wet-bulb depression schedule (based on Hisada et al. 1986)

After that, the values of the dry bulb temperature (DBT) and wet bulb depression (WBD) were determined by using moisture content as an indicator from Tables 3 and 4. These values were combined with the relative humidity values to develop a proposed kiln schedule or drying conditions (for a maximum thickness of 25 mm).

Table 3. Patterned dry bulb temperature schedule

Moisture content (%)	Dry Bulb Temperature for each schedule type (°C)																								
	D 11	D 12	D 13	D 14	D 15	D 21	D 22	D 23	D 24	D 25	D 31	D 32	D 33	D 34	D 35	D 41	D 42	D 43	D 44	D 45	D 51	D 52	D 53	D 54	D 55
60					45					50					55					60					70
				45					50					55					60					70	
50					50					55					60					65					75
			45					50					55					60					70		
40		45		50			50		55			55		60			60		65			70		75	
																					70				
	45		50		55	50		55		60	55		60		65	60		65		70			75		
		50					55					60		65			65		70			75			80
30				55					60												75			80	
	50	55	55		60	55	60	60			60	65	65		70	65	70	70		75			80		
										65				70					75			80			
	55	60	60	60		60	65	65	65		65	70	70			70	75	75			80				
20					65										75					80			85	85	85
	60	65	65	65		65	70	70	70	70	70	75	75	75		75	80	80	80		85	85			
10	70	70	70	70	70	75	75	75	75	75	80	80	80	80	80	85	85	85	85	85	90	90	90	90	90

Source: Hisada et al. (1986)

Table 4. Patterned wet bulb depression schedule

MC (%)	Wet Bulb Depression for each schedule type (°C)																								
	W 11	W 12	W 13	W 14	W 15	W 21	W 22	W 23	W 24	W 25	W 31	W 32	W 33	W 34	W 35	W 41	W 42	W 43	W 44	W 45	W 51	W 52	W 53	W 54	W 55
																									7
80																				5					
															4									7	8
70																			5	6					
60										3				4	5								7	9	10
50					2													5	7	8		7			
									3	4			4	5	7		5				7		9	12	13
45																		7	9	11					
																						10			
				2	3			3				4	5			5	7				9				
40									4.5	6				8	10								13	15	16
			2	3			3	4			4	5	7			7	9	10			12				
35					5														13	14		15			
		2	3	4		3	4	6	7		6	7	9			10	12	13			16				
30										9				12	13								19	20	20
	2	3	5	6		5	6	8	9		9	10	12			14	15	16	18		20	20			
					8																				
25																				19					
	3																								
		6	7	8		8	10	11	12		13	15	16	18	18	20	20	20			25	25	25	25	
	4									14									24						
20																									25
	5				12																30	30	30	30	
		9	10	11		13	15	16	16		20	21	21			25	25	25							
	7													25	23										
15																				25					
	10									20															
		15	16	16	18	21	22	22	21		30	30	30			30	30	30	30						30
10	17																								
	20	25	25	25	25	30	30	30	30	30				30	30					30					

Source: Hisada et al. (1986)

5. Results and Discussions

5.1. Initial moisture content

The initial moisture content of wood is the amount of moisture it contained in its green condition before drying, and is shown in Table 5. It is an important factor in determining the appropriate drying conditions to maintain wood quality, and it influences drying characteristics, drying time and drying rate.

The mean moisture content of *Acacia mangium* is found to be 96.12%, with a minimum of 85.57% and a maximum of 112.61%. Similarly, *Acacia aulacocarpa* has a mean moisture content of 95.47%, ranging from 84.66% to 108.91%. The mean moisture content of *Acacia crassicarpa* is 92.63%, with a minimum of 79.51% and a maximum of 106.24%. These results indicate that among all three Acacia wood species, *Acacia mangium* has a wider range of moisture content than the other two species. Tenorio and Moya (2011) reported that *Acacia mangium* has characteristics such as high moisture content, wet wood content, and high variability in its moisture content. The moisture content of wood varies depending on the heartwood content and density (Simpson, 1991) and anatomical structure (Panshin, 1980).

Table 5. Initial moisture contents of three Acacia species

No.	Species	Moisture Content %			
		Minimum	Maximum	Mean	Standard deviation
1.	*Acacia mangium*	85.57	112.61	96.12	9.55
2.	*Acacia aulacocarpa*	84.66	108.91	95.47	6.32
3.	*Acacia crassicarpa*	79.51	106.24	92.63	6.75

5.2. Evaluation of the drying characteristics

In evaluating drying characteristics, the differences in response of each Acacia species to the drying process are presented as follows.

5.2.1. Initial checks (D_1)

Initial checks, which occur during the early stages of drying, are evaluated on both the wide and end-grain surfaces of the samples. Small checks are observed in all three Acacia species (Figure 3). According to the measurements of the surface checks, *Acacia crassicarpa* is up to 36.6 mm long and 0.48 mm wide, while *Acacia aulacocarpa* is up to 19.87 mm long and 0.42 mm wide. For end checks, the maximum measurements are 20.64 mm in length and 0.59 mm in width for *Acacia aulacocarpa*, 25.63 mm in length and 0.76 mm in width for *Acacia crassicarpa*, and 23.83 mm in length and 0.43 mm in width for *Acacia mangium*.

According to Yang (2012), initial checks (surface checks and end checks) occur because the surface and end of the wood dry faster than the interior. This creates uneven shrinkage due to moisture gradients and internal stresses in the wood resulting from uneven drying, leading to checking. This mainly occurs in conditions of low relative humidity and high temperature, which accelerate moisture movement along the length of the wood compared to its width.

5.2.2. Deformation (D_2)

Deformation, which occurs during the middle stage of drying, is observed in all three Acacia species to varying degrees and is shown in Figure 4. Severe deformations are found in *Acacia mangium*, while only slight deformations are found in *Acacia crassicarpa* and *Acacia* *aulacocarpa.* The average maximum values of deformation are 3.54 mm in *Acacia mangium*, 0.54 mm in *Acacia aulacocarpa,* and 0.49 mm in *Acacia crassicarpa*.

Deformation occurs due to the high initial moisture content of the wood (Yuniarti, 2017). Simpson (1991) and Fu et al. (2023) reported that the difference between radial and tangential shrinkage during the drying process is a factor that causes wood deformation. According to Basri (2019), at the same species, the wetter the wood is, the higher difference between tangential and radial shrinkage. Severe deformation is a serious defect, and the presence of these defects in dried wood makes processing difficult. It affects the wood quality (Yuniarti, 2017).

5.2.3. Honeycombing or Internal checks (D_3)

Further observation is honeycombing, also known as internal checks, which occur at the end of drying. It is one major defect in wood drying. This defect is not visible on the surface and occurs in the inner parts of dried wood along the wood rays. Observations show that *Acacia crassicarpa* exhibits no signs of honeycombing. However, severe honeycombing is observed in *Acacia mangium.* In addition, *Acacia aulacocarpa* exhibits moderate honeycombing. According to Yuniarti (2017), the formation of honeycombing is affected by the initial moisture content of the wood, the wood mass loss, the presence of pith, and the drying rate. Moreover, Bergman (2021) states that it occurs when the drying temperature is high for a long time while the moisture content in the wood is high during the drying process. And, it often develops when the moisture content reduces unevenly or too rapidly during the drying process. Severe honeycombing occurs because of high internal stress during moisture removal, and uneven drying rates or differences in cell wall properties. It reduces the strength of the wood and affects its quality and value of the wood (Phonetip *et al.*, 2017).

Acacia mangium *Acacia aulacocarpa* *Acacia crassicarpa*

Figure 3. End checks in three Acacia species

Acacia mangium *Acacia aulacocarpa* *Acacia crassicarpa*

Figure 4. Honeycombing and deformation in three Acacia species

5.3. Classification of drying characteristics

According to the classification criteria listed in Tables 1 and 2, all three Acacia species are classified into the same class (Class 3) in the initial check assessments. However, there are variations within this class for each species. Regarding deformation, *Acacia mangium* is classified with the highest level (Class 7), while *Acacia aulacocarpa* and *Acacia crassicarpa* are classified with the same lower level (Class 2). With regard to honeycombing, *Acacia crassicarpa* is classified as Class 1, representing the lowest level of honeycombing. *Acacia mangium* is classified as Class 5, indicating the highest severity of honeycombing, while *Acacia aulacocarpa* is classified as Class 3, corresponding to a moderate level of honeycombing.

If the level of deformation and honeycombing is high, it indicates that the wood is prone to collapse (Terazawa, 1986). The wood with a high tendency for honeycombing and deformation should be dried starting at a low temperature with high humidity, especially if its moisture content is above the fiber saturation point (Terazawa, 1986; Basri et al. 1998). Therefore, according to the results, the drying condition for *Acacia mangium* should be milder than those for *Acacia aulacocarpa* and *Acacia crassicarpa*. The types and classes of drying characteristics of three Acacia wood species are summarized and shown in Table 6.

Table 6. Types and classes of drying characteristics of three Acacia wood species

No.	Species	Types and classes of drying characteristics		
		Initial Check	Deformation	Honeycombing
1.	*Acacia mangium*	3	7	5
2.	*Acacia aulacocarpa*	3	2	3
3.	*Acacia crassicarpa*	3	2	1

5.4. Formulation of drying conditions

5.4.1. Determination of patternized kiln schedule codes

Kiln schedule codes represent a series of detailed dry bulb temperature and wet-bulb depression conditions for controlling humidity based on moisture content level at different stages of the drying process. Hisada et al. (1986) developed 25 kiln-drying schedule code patterns, as shown in Figures 1 and 2. These patterns range from the schedule code of D_{11}-D_{15} to D_{51}-D_{55} for dry-bulb temperature (DBT), and from the schedule code of W_{11}-W_{15} to W_{51}-W_{55} for wet-bulb depression (WBD). A higher schedule code represents a severer drying schedule.

Based on the highest level of drying characteristics and the initial moisture content for each Acacia wood species, the drying schedule codes for dry bulb temperature and wet bulb depression are determined as $D_{23}W_{24}$ for *Acacia mangium*, $D_{33}W_{34}$ for *Acacia aulacocarpa*, and $D_{34}W_{34}$ for *Acacia crassicarpa*.

5.4.2. Determination of dry bulb temperature values

According to the schedule codes, the sequential changes of dry bulb temperature at corresponding moisture content during the drying process for each Acacia species are determined and presented in Tables 7 to 9.

Table 7. Sequential changes of dry bulb temperature at corresponding moisture content for *Acacia mangium.*

Step	Moisture Content (%)	Dry Bulb Temperature (˚C)
1	Above 40	50
2	40-30	55
3	30-25	60
4	25-20	65

5	20-15	70
6	<15	75

Table 8. Sequential changes of dry bulb temperature at corresponding moisture content for *Acacia aulacocarpa.*

Step	Moisture Content (%)	Dry Bulb Temperature (˚C)
1	Above 40	55
2	40-30	60
3	30-25	65
4	25-20	70
5	20-15	75
6	<15	80

Table 9. Sequential changes of dry bulb temperature at corresponding moisture content for *Acacia crassicarpa*

Step	Moisture content (%)	Dry Bulb Temperature (°C)
1	Above 45	55
2	45-35	60
3	35-30	65
4	30-20	70
5	20-15	75
6	<15	80

5.4.3. Determination of wet bulb depression values

Similarly, the sequential changes of wet bulb depression at corresponding moisture content during the drying process are also determined using the schedule code, and are presented in Tables 10 and 11.

Table 10. Sequential changes of wet bulb depression at corresponding moisture content for *Acacia mangium.*

Step No	Moisture content %	Wet Bulb Depression (°C)
1	Above 50	3
2	50-40	5
3	40-35	7
4	35-30	9
5	30-25	12
6	25-20	16
7	20-15	21
8	<15	30

Table 11. Sequential changes of wet bulb depression with corresponding moisture content for *Acacia crassicarpa* and *Acacia aulacocarpa.*

Step	Moisture content %	Wet bulb depression (°C)
1	Above 60	4
2	60-50	5
3	50-40	8
4	40-30	12
5	30-25	18
6	25-15	25

7	<15	30

The values of the relative humidity are further determined by combinations of dry bulb temperature and wet bulb depression values.

5.4.4. Determination of moisture contents at each stage of the drying process

The moisture contents are systematically adjusted at each stage of the drying process. The corresponding moisture contents for each Acacia species are given in Table (12).

Table 12. Moisture contents at each stage of drying for three Acacia wood species

Step	Moisture content at each stage of drying process (%)		
	Acacia mangium	*Acacia aulacocarpa*	*Acacia crassicarpa*
1	Above 50	Above 60	Above 60
2	50 ~ 40	60 ~ 50	60 ~ 50
3	40 ~ 35	50 ~ 40	50 ~ 40
4	35 ~ 30	40 ~ 30	40 ~ 30
5	30 ~ 25	30 ~ 25	30 ~ 20
6	25 ~ 20	25 ~ 20	20 ~15
7	20 ~15	20 ~15	15 to Final
8	15 to Final	15 to Final	

Finally, based on the above determinations, the drying conditions, including dry bulb temperature, wet bulb depression, and moisture content levels, are re-evaluated in detail and presented as kiln drying schedules in Tables 13 to 15.

Table 13. Description of the proposed dry kiln schedule ($D_{34}W_{34}$) for *Acacia crassicarpa*

Step	Moisture content (%)	DBT (˚C)	WBD (˚C)	RH (%)
1	Above 60	55	4	81
2	60 ~ 50	55	5	76
3	50 ~ 40	60	8	66
4	40 ~ 30	65	12	54
5	30 ~ 20	70	18	40
6	20 ~15	75	25	28
7	15 to Final	80	30	22

This kiln schedule, $D_{34}W_{34}$, is designed with moderate drying conditions to achieve faster moisture diffusion and surface evaporation. The process starts at a moderate initial dry bulb emperature of 55°C until the moisture content reaches 50%. The relative humidity gradually decreases to maintain efficient drying. As the drying process continues, the moisture content of the wood decreases, and the dry bulb temperature gradually increases from 60°C to 75°C. As soon as the wood reaches 15% moisture content, the dry bulb temperature is increased to 80% until the desired moisture content is reached.

Table14. Description of the proposed dry kiln schedule ($D_{33}W_{34}$) for *Acacia aulacocarpa*

Step	Moisture content (%)	DBT(˚C)	WBD(˚C)	RH(%)
1	Above 60	55	4	81
2	60 ~ 50	55	5	76
3	50 ~ 40	55	8	64
4	40 ~ 30	60	12	52
5	30 ~ 25	65	18	38

6	25 ~20	70	22	31
7	20 ~15	75	25	28
8	15 to Final	80	30	22

DBT= Dry Bulb Temperature, WBD = Wet Bulb Depression, RH = Relative Humidity

In this kiln schedule, $D_{33}W_{34}$, the initial dry bulb temperature of 55°C is held constant until the moisture content reaches 40%. The relative humidity is then gradually reduced to maintain a fast drying rate. As the moisture content decreases, the dry bulb temperature is increased from 60°C to 80°C to achieve faster moisture diffusion from the interior to the surface of the wood.

According to the results, the drying conditions for *Acacia crassicarpa* (Table 13) and *Acacia aulacocarpa* (Table 14) are similar up to 50% moisture content. After that point, dry bulb temperature increases slightly in *Acacia crassicarpa*. From 15% moisture to the final stage, drying conditions are similar for both species. The drying conditions for *Acacia aulacocarpa* wood are slightly milder than those for *Acacia crassicarpa* wood. This may be due to the fact that *Acacia aulacocarpa* occurs more honeycombing during the drying process compared to *Acacia crassicarpa*. However, since *Acacia crassicarpa* and *Acacia aulacocarpa* are the same species, if their densities are nearly the same, these lumbers can be dried together using milder drying conditions, kiln schedule $D_{33}W_{34}$. If the wood does not develop checks and deformation using this schedule, drying conditions, kiln schedule $D_{34}W_{34}$, with a slightly high temperature and relative humidity value, should be used to reduce production cost and energy consumption.

Table15. Description of the proposed dry kiln schedule ($D_{23}W_{24}$) for *Acacia mangium*

Step	Moisture content (%)	DBT(˚C)	WBD(˚C)	RH(%)
1	Above 50	50	3	85
2	50 ~ 40	50	5	75
3	40 ~ 35	55	7	63
4	35 ~ 30	55	9	60
5	30 ~ 25	60	12	52
6	25 ~ 20	65	16	43
7	20 ~15	70	21	33
8	15 to Final	75	30	20

DBT= Dry Bulb Temperature, WBD = Wet Bulb Depression, RH = Relative Humidity

This schedule, $D_{23}W_{24}$, starts with a moderately low temperature and moderately high relative humidity to help moisture diffusion and evaporate more quickly from the surface. The initial dry bulb temperature of 50°C is held constant until the moisture content reaches 40%, with the relative humidity is then gradually decreased to maintain a fast drying rate. As the drying process continues, the moisture content of wood decreases, and the dry bulb temperature is gradually increased from 55°C to 75°C until the desired final moisture content is reached.

Based on the drying defects observed in the "Quick Drying Test", the three Acacia species tested can be classified as *Acacia mangium* is a refractory timber, *Acacia crassicarpa* and *Acacia aulacocarpa* are moderately refractory timbers. Therefore, in determining drying conditions for these three Acacia species, it is necessary to consider not only initial checks and deformation, but also honeycombing. Terazawa (1965) stated that initial checking is strictly related to initial relative humidity and related to initial temperature, but is less related to final temperature and is not related to final relative humidity. Deformation and honeycombing are related to the initial temperature and initial relative humidity, and not related to the final relative humidity. The final temperature is related to honeycomb, but less related to deformation. Bergman (2021) reported that if relative humidity is too low in the early stages of drying, excessive shrinkage can occur, leading to surface and end checking, and if the temperature is too high, collapse, honeycomb, or strength reduction can occur. Effah (2012) stated that hardwoods dry slowly and have less product loss when the initial temperature is low and the initial humidity is high in the drying process.

Therefore, a moderately high initial relative humidity should be used at the start of kiln drying to prevent the occurrence of surface and end checks. Additionally, it is important to avoid high temperature to prevent honeycombing and deformation. These drying conditions are the mildest possible settings, designed starting with moderately low temperature and moderately high relative humidity based on the most severe defects found in the test. Therefore, it would minimize drying defects with moderately rapid drying.

The results of the quick drying test conducted on the three Acacia species are summarized and presented in Table 16. This table includes initial moisture content, classification of drying characteristics, drying conditions, and kiln schedule code.

Table 16. Summary of results from quick drying test of three Acacia species

Species	Initial moisture content (%)	Classification of drying characteristics			Drying conditions (ºC)			Schedule codes
		D_1	D_2	D_3	Initial DBT	Initial WBD	Final DBT	
Acacia mangium	96.12	3	7	5	50	3	75	$D_{23}W_{24}$
Acacia aulacocarpa	95.47	3	2	3	55	4	80	$D_{33}W_{34}$
Acacia crassicarpa	92.63	3	2	1	55	4	80	$D_{34}W_{34}$

Remarks: D_1 = Initial Checks, D_2= Deformation, D_3 = Honeycomb
DBT= Dry Bulb Temperature, WBD = Wet Bulb Depression

6. Conclusion

Based on the drying characteristics and drying conditions of the three Acacia wood species, the following conclusions can be drawn:

According to research findings, three Acacia wood species, *Acacia mangium, Acacia crassicarpa* and *Acacia aulacocarpa*, are susceptible to drying defects during the drying process. Out of these three species, *Acacia crassicarpa* is found to be the least susceptible to drying defects, as it shows no signs of honeycomb (class 1), class 2 in deformation, and class 3 in initial checks. On the other hand, *Acacia mangium* is the most susceptible to drying defects, exhibiting severe deformation (class 7), honeycombing (class 5), and initial checks (class 3). *Acacia aulacocarpa* is more susceptible to drying defects than *Acacia crassicarpa* but to a lesser extent than *Acacia mangium,* showing honeycombing (class 3), deformation (class 2), and initial checks (class 3).

Based on the drying characteristics, three drying conditions are formulated. For *Acacia mangium* lumber, which is 25 mm thick, the drying condition is to start at an initial temperature of 50°C and gradually increase to a final temperature of 75°C. The wet bulb depression should range from 3 to 30°C, and the relative humidity should range from 85 to 20%. Similarly, for *Acacia aulacocarpa* lumber, which is also 25 mm thick, the drying condition is to start at an initial temperature of 55°C and gradually increase to a final temperature of 80°C. The wet bulb depression should range from 4 to 30°C, and the relative humidity should range from 81% to 22%. *Acacia crassicarpa* lumber, which is also 25 mm thick, should be kiln-dried using drying condition with a temperature range of 55–80°C, wet bulb depressions of 4–30°C, and a relative humidity of 81% to 22%. It is recommended that at the end of the kiln drying process, equalization and conditioning treatments should be performed to achieve uniform moisture content and to relieve drying stress that occurs within and among the lumbers.

These three drying conditions are only for kiln drying of 25 mm thick lumber, and can be modified during the kiln-drying process and adjusted to suit the condition of the drying kiln and the dimensional sizes of lumber. These research findings will help not only to predict which drying characteristics will occur when drying 25 mm thick lumbers made from the three tested Acacia wood species but also to increase the quality, processing efficiency of these timbers, and the profitability of the industry. Although drying characteristics are essential to evaluate the end use of the species, other technological knowledge on physical and mechanical properties, durability, and anatomical properties should also be considered.

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