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Dimensional Changes and Mechanical Properties of Acetylated Three Lesser Used Timber Species of Myanmar

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Acetylation နည်းဖြင့် ဆေးသွင်းထားသော မြန်မာနိုင်ငံမှ လူသုံးနည်းသစ် (၃)မျိုး၏ အတိုင်းအတာပြောင်းလဲမှု နှင့် သစ်အင်အားကို လေ့လာခြင်း

ချိုချိုဝင်း၊ လက်ထောက်သုတေသနအရာရှိ၊ သစ်တောသုတေသနဌာန
ပါမောက္ခဦးဝင်းကြည်၊ အငြိမ်းစားပါမောက္ခချုပ်၊ သစ်တောတက္ကသိုလ်

စာတမ်းအကျဉ်း

မြန်မာနိုင်ငံမှ လူသုံးနည်းသစ် (၃) မျိုးအား Acetylation နည်းဖြင့် ဆေးသွင်းပြုပြင် ပြီး ၎င်းတို့၏ အတိုင်းအတာပြောင်းလဲမှုနှင့် သစ်အင်အားကို စမ်းသပ်လေ့လာခဲ့ပါသည်။ လူသုံးနည်းသစ် (၃)မျိုး ဖြစ်သည့် နှော၊ လယ်စ နှင့် ပျဉ်းမတို့အား Acetic anhydride ကို acetic acid အကူဖြင့် လေဟာနယ်နှင့် ဖိအားနည်းကိုအသုံးပြု၍ ဆေးသွင်းပြုပြင်ခဲ့ပါသည်။ ဆေးသွင်းပြီးသစ်နမူနာများ၏ ဆေးဝင်မှုပမာဏကို တိုင်းတာပါသည်။ ဆေးသွင်းပြီး သစ်နမူနာများ၏ ကျုံ့မှု၊ ကြွမှုနှင့် အတိုင်းအတာပြောင်းလဲမှုသည် ဆေးမသွင်းသည်ထက် သိသာစွာ လျော့ကျကြောင်းတွေ့ရပါသည်။ ဖြက်အတိုင်းကျုံ့မှုတွင် နှောသစ်နမူနာတုံးများသည် ၅၈%၊ လယ်စ သစ်နမူနာတုံးများသည် ၃၇% နှင့် ပျဉ်းမသစ်နမူနာတုံးများသည် ၆၅%အထိ လျော့ကျ သွားကြောင်းတွေ့ရပါသည်။ ကြွမှုဟန့်တားခြင်း ညွှန်းကိန်း တွက်ချက်ရာတွင် နှောသည် ၅၃%၊ လယ်စသည် ၃၇% နှင့် ပျဉ်းမသည် ၇၀% အသီးသီးရှိကြောင်း တွေ့ရပါသည်။ သစ်အင်အားစမ်းသပ်ချက်အရ သစ်ကြောကိုထောင့်မှန်ကျ အတိုင်းဖိအားနှင့် မာကြောမှုအင်အား မှအပ ကျန်အင်အားများတိုးလာသည်ကို တွေ့ရပါသည်။

Dimensional Changes and Mechanical Properties of Acetylated Three Lesser -Used Timber Species of Myanmar

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Abstracts

In this study, the dimensional changes and mechanical properties of three lesser -used timber species (LUS) which were treated through acetylation using Aceticanhydride. The three LUS namely *Adina cordifolia* (Hnaw), *Lagerstromia tomentosa* (Leza) and *Legerstromia speciosa* (Pyinma) were impregnated with acetic anhydride and acetic acid as catalyst by using vacuum-pressure method. After acetylation, radial shrinkage and tangential shrinkage of acetylated Hnaw, Leza and Pyinma samples were significantly different from those of non-acetylated samples. Tangential shrinkage of acetylated Hnaw reduced 58% than that of non-acetylated samples. Tangential shrinkage of acetylated Leza reduced 37% than that of non-acetylated samples. Tangential shrinkage of acetylated Pyinma reduced 65% than that of non-acetylated samples. Maximum ASE (Anti Swelling Efficiency) can be reached up to 53% for Hnaw, 37% for Leza and 70% for Pyinma, by acetylation treatment after 24 hours soaking/drying procedure. Mechanical properties such as FS@PL, MOR and MOE in static bending test, FS@PL and MCS in compression parallel to grain test, FS@PL in compression perpendicular to grain test and Hardness of radial, tangential and end surfaces were carried out for this study. The results revealed that all the strength properties of test species were significantly improved by acetylation expect compression perpendicular to grain test and hardness test.

Key words: Acetylation, Modification, Dimensional changes, Anti Swelling Efficiency, Lesser used species

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1. Introduction

Wood normally shrinks as it dries and swells as it absorbs moisture. These changes in its dimensions are of importance to anyone who uses wood because wood readily takes on or gives off moisture, even from the atmosphere. Successful use of wood for exacting purposes under wide variations in atmospheric humidity shows that the problems arising from the shrinking and swelling of wood can be surmounted.

Good practice, in general, requires that efforts be made to reduce the changes in dimensions that take place while wood is in use and to minimize their effects by methods of installation and construction. Fortunately, wood is somewhat plastic, so that it can conform to a certain amount of dimensional changes without serious damage. On the other hand, the stresses developed in shrinking or swelling may cause a great deal of damage. The use of insufficiently dried lumber that shrinks under service conditions commonly results in subsequent checking, opening of joints, loosening of nails, and the warping and distortion of wood structures as a whole. If lumber is dried too far below the moisture content it will reach in use, swelling may cause drawers, windows, and doors to stick.

In the light of updated technology, there are ways and means to improve the dimensional stability of timber. In fact, exclusion of moisture absorption by the wood is the basic requirement for dimensional stability of timber. Likewise, air drying and kiln drying the wood do not prevent the wood from subsequently gaining or losing moisture (Win Kyi-2, 1985). There have been many studies aimed at stabilizing the cell wall so that shrinkage of wood can be controlled. Thermosetting resins that are highly water resistant are normally used for this purpose. Resin–treated wood, compressed wood, wood treated with polyethylene glycol, and wood polymer composites are some of the means used to reduce or eliminate cell wall shrinkage. However, none of these methods has been put into practical use due to economical and technical considerations.

The replacement of some hydroxyl groups on the cell wall polymers with bonded acetyl groups reduces the hydroscopicity of wood. There are some competing effects influencing the mechanical properties of wood when it is acetylated. It was noted that a study of the scientific literature gives a complicated picture with some workers reporting a slight increase in the mechanical properties and some a slight decrease.

In this study, three Myanmar Lesser Used Timber Species were acetylated with acetic anhydride and their shrinkage and swelling properties and dimensional stabilities were studied. The effects of acetylation on mechanical properties were also studied.

The objectives of this study are to investigate the changes in dimensional stability of acetylated wood and to study the effects of acetylation on the mechanical properties of wood.

2. Literature Review

2.1. Dimensional changes of acetylated wood

The dimensional changes that accompany the shrinking and swelling of wood are major sources of both visual and structural problems in furniture. Shrinking and swelling occur as the wood changes moisture content in response to daily as well as seasonal changes in the relative humidity of the atmosphere, i.e., when the air is humid, wood adsorbs moisture and swells; when the air is dry, wood loses moisture and shrinks.

Wood is a hygroscopic material which loses and gains moisture as a result of changes in humidity. The effects of swelling and shrinking depend on uptake of water molecules by the cell wall components of wood. As water molecules penetrate into the cell wall and push the cellulose fibrils apart by inserting themselves between the hydroxyl groups of cellulose, wood becomes swollen. When the water molecules leave the cell wall later, the wood shrinks (Skaar, 1988).

Wood is an anisotropic material; that is, its dimensions change differently in three directions: tangentially, radially, and longitudinally. Tangential dimensional change has the highest rate of change due to parallel orientation of microfibrils along the axis of the cell wall. Shrinkage in the radial direction is the second largest, while longitudinal shrinkage is negligible for the most practical applications. Dimensional stabilization of wood is needed for special applications.

A dimensional stability treatment is one that reduces or prevents swelling in wood, no matter how long it is contact with moisture or liquid water (Rowell and Youngs, 1981). Various finishes and treatments may be used to slow this process, but, in general, they do not stop it (Carl A. Eckelman,).

Stamm (1983) stated that the dimensional stability of wood can be much improved by impregnation treatments. When the wood cell wall is previously swollen with wax, sugars and salts, it can hardly swell with moisture adsorption. In most cases, however, the impregnating substances are deliquescent and water-soluble. This is a problem when the treated wood is used in humid or wet conditions.

Dimensional stabilization of wood specimen was generally evaluated by measuring ASE in most research papers. The higher the ASE values, the more dimensional stabilized the treated specimens become compared to untreated control specimens.

Militz *et al* (1997) stated that wood modification can improve the dimensional stabilization of wood. One of the aims of modification of wood is the improvement of the dimensional stability of the wood. They also stated that the acetylation can improve dimensional stability in solid wood and other lignocellulosic composite. Hydrophobicity and anti-shrink efficiency (ASE) of wood caused by the acetylation is due to chemical blocking of hydroxyl groups.

When wood is acetylated it is far less susceptible to shrinking and swelling in the presence of varying atmospheric conditions. The reason for this is simply explained by Rowell (1984) that the cell wall is now filled with chemically bonded acetyl groups which take up space within the cell wall. As a consequence, the wood is already in a swollen condition, the extent of which depends upon the level of modification, there is very little residual swelling when the wood is soaked in water.

The possibility that reduced swelling due to chemical modification may be related to the WPG, or bulking of the cell wall (Stamm and Tarkow, 1974; Hill and Jones, 1996; Li *et al*. 2000). Invariably, this swelling is determined by measuring the external dimensions of oven- dry wood samples before and after modification.

2.2. Mechanical properties of acetylated wood

According to Rowell (1996), it was noted that a study of the scientific literature gives a complicated picture with some workers reporting a slight increase in the mechanical properties and some a slight decrease. Because of many different ways in which the results can be presented, this accounts for at least some of the confusion.

There are some competing effects influencing the mechanical properties of wood when it is acetylated.

Bending strength and E-modulus in bending were not influenced while shear strength was slightly reduced (Akitsu *et al*. 1993; Goldstein *et al*., 1961; Dreher et al., 1964; Larsson and Tillman, 1989; Militz, 1991; Rowell, 1991). Militz (1991) reported a slight increase in MOR and a small decrease in MOE when beech wood was acetylated. Birkinshaw and Hale (2002) found that acetylation did not significantly affect the mechanical properties of the softwoods studied (pine, spruce, larch). Bongers and Beckers (2003) performed a comprehensive analysis of the mechanical properties of wood, variable results were obtained, with some species showing increases in some properties and other decreases, but results were consistent within a species. Acetylated samples were also found to be less susceptible to deformation when subjected to varying RH.

In a recent study of the mechanical properties of *structural size* pieces of acetylated wood, it was reported that acetylation made little difference to the mean strength properties. (Jorissen *et al.* 2005). However, due to a greater variability in strength properties, the characteristic value was found to drop by about 35%. It was recommended that a grading system be employed after acetylation to overcome this disadvantage. In a study of the effect of acetylation upon Scots pine and lime (*Tilia vulgaris*), there was not found to be significant difference compared to unmodified controls (Rowell and Banks, 1987).

Acetylation of wood results in a decrease in equilibrium moisture content at a given relative humidity, which in turn yields a concomitant increase in tensile strength, MOR and MOE (Dinwoodie 2000). Furthermore, the wood density influences the mechanical properties. Due to acetylation wood swells because of added acetyl groups, while weight is increased to a higher percentage and, consequently, the density increases.

It was also noted that as the wood swells as a result of the presence of bonded acetyl groups in the cell wall, a given cross - sectional area of modified wood would therefore contain fewer fibres which has a negative effect on mechanical properties, mainly on the shear strength. Swelling also results in lesser lignocellulosic fibres per cross- section, For E-modulus the positive and negative effects seem to keep each other in balance (lower moisture content and higher density (+), lesser fibres per volume (-). For compression strength and hardness the positive effects overrule the negative ones and they are slightly improved.

3. Material and Methods

3.1. Sample preparation

Three Lesser Used Timber Species were tested in this study. They are

(1) *Adina cordifolia* Hk. F. (Hnaw)
(2) *Lagerstroemia tomentosa* Presl. (Leza) and
(3) *Lagerstroemia speciosa* (L) Pres. (Pyinma)

Wood samples were obtained from the Wood Preservation Section. They were collected from Phyukun and Kabaung Reserved Forest, Taungoo Forest District, Bago Division, under the ITTO Project entitled “Introducing Myanmar’s Lesser- used Timber Species to the World Market”. These wood samples had been authenticated and identified at the Herbarium Section and Wood Anatomy Section of Forest Research Institute (FRI), Yezin. The tree number, bolt number and section number (i.e. distance from pith) of the wood samples were carefully marked and stored at the Wood Preservation Section of FRI, Yezin.

The preparation of tested samples for were based on BS (British Standard) 373-1957. The method of tests was conducted according to ASTM (American Society for Testing and Material) standard D-143-52 (Reapproved, 1965). For all tested species, the size and number of samples for each test are shown in Table (1and 2).

Table (1) Size and Number of Samples for Dimensional Stability Test

Experiment	Sample size (r, t, l), (mm^3)	Number of Samples		
		For MC	Control	Treatment
1) Tangential shrinkage	25 x 25x 50	10	10	10
2) Radial Shrinkage	25 x 25 x 50	10	10	10
3) Longitudinal Shrinkage	25 x 25 x 100	10	10	10
4) Swelling	25 x 25x 10	10	30	30

Table (2) Size and Number of Samples for mechanical test for each tested species

Experiment	Sample size (r, t, l) (mm^3)	Numbers of Samples	
		Control	Treatment
Static Bending	20 x 20 x 300	30	30
Compression parallel to grain	20 x 20 x 80	30	30
Compression perpendicular to grain	20 x 20 x 60	30	30
Hardness	20 x 20 x 60	30	30

3.2. Acetylation of tested samples

The prepared samples were impregnated with acetic anhydride by the catalyst of acetic acid using vacuum-pressure method. The acetylation procedure was carried out under the condition of temperature between 80-120°C and 15 psi pressure for 180 minutes (Beckers and Militz 1994, Beckers *et al.* 1994). Acetic anhydride (BDH, Chemicals Ltd Poole England) and acetic acid (as a catalyst) were mixed in the ratio of 3:1. The control specimens were water impregnated.

After acetylation, the samples were soaked in de-ionized water to remove un-reacted acetic anhydride and acetic acid by-product within a few days until the smell of these chemicals was no longer detected. The weights after acetylation were recorded. The percentages of weight gains (WPG) were calculated the following formula.

$WPG = (W_t - W_u)/ W_u \times 100$ ……. eq: (3.1)

Where,

WPG = percentages of weight gains,

W_u = the dry weight before treatment and

W_t =after treatment

3.3. Testing Dimensional Changes

3.3.1. Shrinkage of acetylated samples

Shrinkage will be determined by measuring the external dimensions (longitudinal (*l*), radial (*r*) and tangential (*t*) of the tested sample. From the measurement of external dimensions, the radial and tangential shrinkage values of wood samples were also determined by the following:

S_R (%) = $(R_1 – R_0)/ R_0 * 100$ ------------ eq: (3.2)
S_T (%) = $(T_1 – T_0)/ T_0 * 100$ ------------ eq: (3.3)

where,

S_R= Radial Shrinkage of tested samples
S_T= Tangential Shrinkage of tested samples
R_0 = Radial measurement of tested samples before treatment (oven –dry)
T_0 = Tangential measurement of tested samples before treatment (oven –dry)
R_1 = Radial measurement of tested samples after treatment (oven –dry)
T_1 = Tangential measurement of tested samples after treatment (oven –dry)

3.3.2. Swelling of acetylated samples

For measuring swelling, the tested samples were soaked in water and the external dimensions were measured at 4- hour intervals.

Dimensional stability is reported as the swelling coefficient (S). The swelling coefficient (S) can be calculated as shown in the following.

S (%) = [(Vwet – Vdry) / Vdry] x 100 ------------- eq: (3.4)

where,

Vwet is the water saturated wood volume and
Vdry is the volume of the same sample after oven drying.

After that, a much better indicator for dimensional stability, the anti- swelling efficiency abbreviated as ASE, was determined by the following equation (Hill and Jones 1996).

ASE (%) = $[(S_{unmod} – S_{mod}) / S_{unmod}] \times 100$ ------------- eq: (3.5)

where,

S_{unmod} is the swelling coefficient of unmodified wood and

S_{mod} is the swelling coefficient of modified wood.

3.4. Testing mechanical properties

Shimadzu Autograph Universal Testing Machine was used for testing the mechanical properties. All the mechanical properties' testing were carried out in Timber Mechanic Section of FRI.

3.4.1. Static bending test

Data obtained from static bending tests were used in calculating three values: fiber stress at proportional limit (FS@PL), modulus of elasticity (MOE) and modulus of rupture (MOR).

FS @ PL = $1.5\ P'L/bd^2$ ---------------- eq: (3.6)
MOE = $P'L^3/4Dbd^2$ ---------------- eq : (3.7)
MOR = $1.5\ PL/bd^2$ ------------- eq: (3.8)

Where,

FS@PL = the fiber stress at proportional limit (N/mm^2),
P' = proportional load (N),
L = the span of the support (mm),
b = the width of the specimen (mm) and d = the depth of the specimen
D = deflection at proportional limit
P = maximum load at which the specimen comes across with failure

3.4.2. Compression parallel to grain test

For this test, two properties, i.e. maximum crushing strength and fiber stress at proportional limit, are evaluated. It is calculated by the formula:

MCS = P/A ------------- eq: (3.9)
FS @ PL = P'/A---------------- eq: (3.10)

where

MCS = maximum crushing strength
FS@PL = fiber stress at proportional limit
P = maximum load
P' = load at proportional limit
A = area of cross- section

3.4.3. Compression perpendicular to grain test

The fiber stress at proportional limit is the only value computed in this test. It is calculated by the formula:

FS@PL = P'/A ------------- eq: (3.11)

where

P' = load at proportional limit
A = the area under the plate

4. Results and Discussion

4.1. Shrinkage of wood due to acetylation

The shrinkage values from green to oven- dry of acetylated and un-acetylated wood samples of the tested species are shown in **table 3**. According to this table, it was found that all the acetylated wood samples have less shrinkage than non-acetylated samples.

Table 3. The Shrinkage (green to oven – dry) of tested species

Species	Treatment	WPG (%)	Average Shrinkage (Green to oven dry)		
			Tangential (%)	Radial (%)	Longitudinal (%)
Hnaw	Control	-	7.22	4.243	0.26
	Treat I	22.231	3.75	2.04	0.23
	Treat II	29.217	3.04	1.82	0.17
Leza	Control	-	6.12	4.67	0.23
	Treat I	21.073	3.99	3.08	0.21
	Treat II	21.554	3.84	2.12	0.33
Pyinma	Control	-	6.31	3.92	0.30
	Treat I	16.505	2.83	2.12	0.14
	Treat II	26.974	2.20	1.49	0.23

According to table 3, the average tangential, radial and longitudinal shrinkage (green to oven- dry) of untreated Hnaw are found to be 7.22%, 4.24% and 0.26%, respectively. After acetylation those of Hnaw was reduced to 3.04%, 1.82% and 0.17%. Thus, tangential shrinkage of Hnaw is reduced to 58% and 57% for radial shrinkage. It shows that acetylation significantly affected the shrinkage of Hnaw.

It can also be seen that, the mean shrinkage (green to oven- dry) of untreated Leza was found to be 6.12% for tangential, 4.09% for radial and 0.23% for longitudinal dimensions. After acetylation, the average tangential shrinkage of acetylated samples decreases to 3.84% and 2.12% for radial dimension. It reduced to 37% for tangential and 48% for radial. It was also found that acetylation significantly affected the shrinkage of Leza.

The average shrinkage (green to oven- dry) of untreated Pyinma was found to be 6.3% for tangential, 3.9% for radial and 0.3% for longitudinal dimensions. After acetylation the average tangential shrinkage of Pyinma was reduced to 2.2% and 1.49% for radial. The shrinkage of Pyinma can be reduced to 65% for tangential and 61% for radial dimension. Therefore, it was found that acetylation significantly affected on shrinkage of Pyinma.

In order to clearly reveal the effectiveness of treatment, the shrinkage of acetylated samples and un-acetylated samples are graphically shown in figures 1**.**

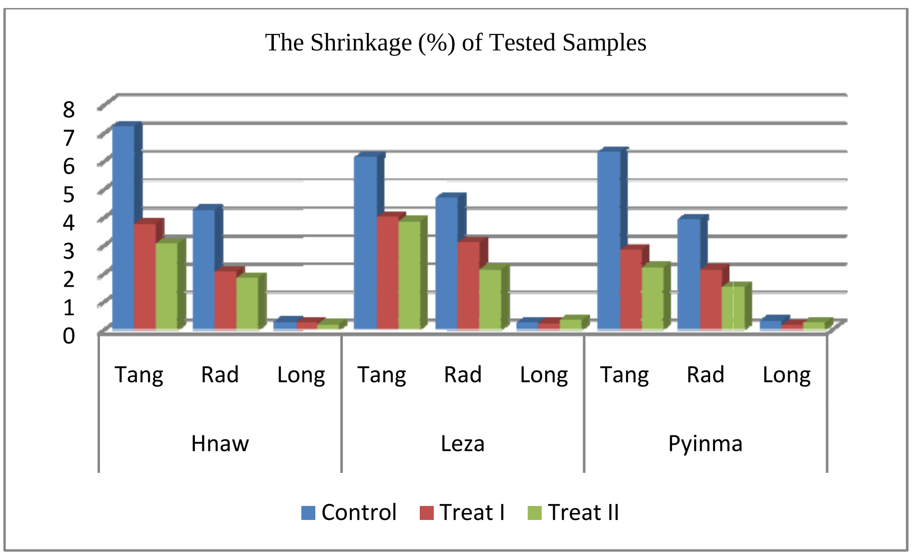

Figure 1. The average shrinkage (green to oven- dry) of non-acetylated and acetylated tested samples

4. 2. Swelling of wood due to acetylation

In this study, swelling is determined by measuring the external dimensions of oven-dry wood samples before and after modification. The relationship between swelling caused by acetylation and reduction of swelling is shown in table 4. The absolute swelling of the untreated samples and acetylated samples are included in those tables. According to this table it can be found that the amounts of water adsorbed by the acetylated samples were slightly reduced compared with un-acetylated ones at various dipping time in water reduced by treatments for all tested species.

Acetylation treatment resulted in lower moisture uptake than corresponding one. However, little swelling can occur when water permeates the acetylated wood. Acetylated wood can absorb water through capillary action and to some extent, in the cell wall. Since the water molecule is smaller than the acetyl group, some swelling can occur in "completely acetylated wood" but swelling does not exceed the elastic limit of the cell wall. Thus, the swelling and shrinkage of wood cannot be prevented completely by a bulking reagent whose molecules are larger than those of water.

Table 4. The Swelling (%) of tested species

Species		Treatment	Swelling (%) at individual soaking time (hour)					
			4	8	12	16	20	24
Hnaw	Tangential	Control	6.41	7.69	7.10	7.25	7.47	7.42
		Treatment	6.01	6.84	6.69	7.46	7.21	7.21
	Radial	Control	3.85	3.78	3.74	3.73	3.66	3.65
		Treatment	3.02	3.11	3.29	3.33	3.43	3.44
Leza	Tangential	Control	8.08	8.51	9.09	9.93	9.62	10.92
		Treatment	3.13	4.66	4.11	5.61	6.20	6.92
	Radial	Control	3.34	5.12	4.96	6.11	7.54	7.91
		Treatment	3.14	4.06	4.94	5.79	5.83	6.12
Pyinma	Tangential	Control	3.58	5.09	4.61	5.69	5.35	5.48
		Treatment	2.45	3.37	2.82	3.53	3.32	3.27
	Radial	Control	3.57	4.69	4.13	5.34	5.00	5.26
		Treatment	2.01	2.53	2.72	2.75	2.63	2.77

In order to clearly reveal the changes in swelling at different soaking time, swelling of non-acetylated samples and acetylated samples are shown in figure 2, 3 and 4. It was found that clear correlation was obtained between the effects of acetylation on the swollen dimensions of wood.

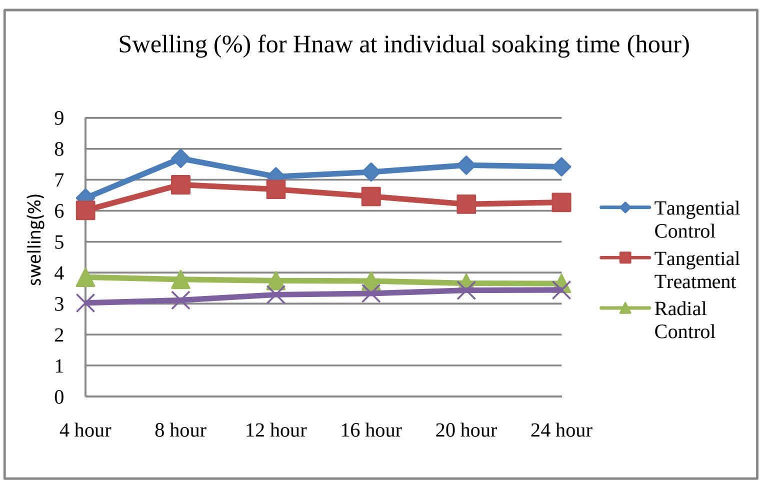

Figure2. Swelling at different soaking time of non-acetylated and acetylated samples

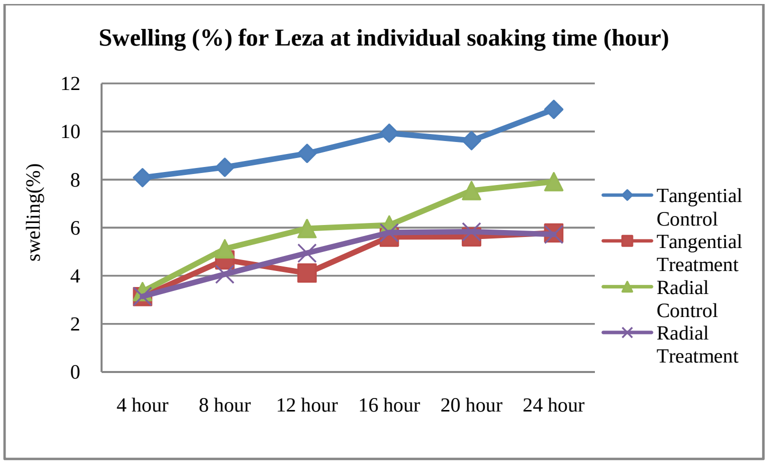

Figure 3.Swelling at different soaking time of non-acetylated and acetylated samples

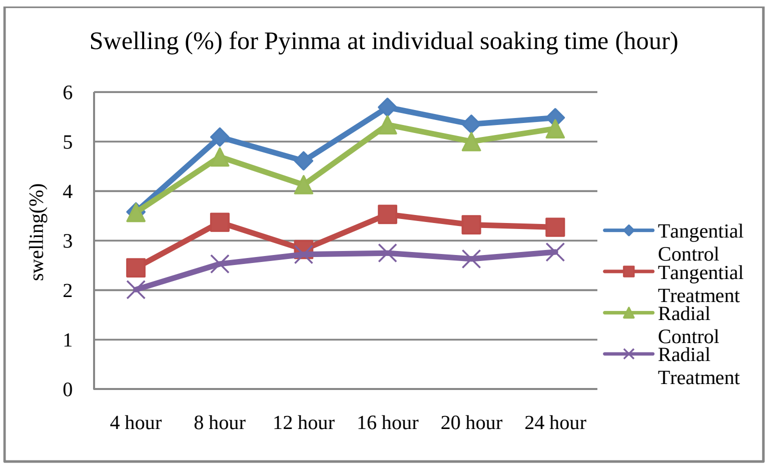

Figure 4.Swelling at different soaking time, of non-acetylated and acetylated samples

4.3. Anti-swelling efficiency (ASE) of tested species

Dimensional changes due to modification have been determined from external volumes of samples before and after modification. Anti-swelling efficiency (ASE) was determined from the oven dry and saturated dimensions as an index to dimensional changes. The higher the ASE values, the more dimensional stabilized the treated specimens become compared to untreated control specimens Hill et al (2004).

Table 5. Anti-swelling efficiency (ASE) of acetylated tested species

Species	WPG (%)	
	25-29 %	22-24%
Hnaw	53.40	51.06
Leza	59.43	56.87
Pyinma	70.31	68.64

In this study, ASE of Hnaw was found to be 51% at 22% WPG and 53.4% at 29% after 24 hours of water- soaking. As for Leza, it was found that ASE was 57% for 22% of WPG and 60% at WPG of 29% after 24 hours of water- soaking. The ASE of Pyinma was found to be 70.31% at average WPG of 29% and 68.64% at average WPG of 24 respectively, after 24 hours of water- soaking.

Swelling of the cell wall that decreased in dimensional changes of acetylated wood because occupying of spaces within the cell wall that results in blocking of water and other molecules to the cell wall that leads to a reduction in the hydroscropicity of the wood.

Tarkow et.al.(1950) reported an improvement in the dimensional stability of about 70% for maple and balsa wood acetylation to a WPG 20% and Spruce acetylated wood to WPG 26% (Larsson, 1998). Popper and Bariska (1975) reported a 75% of improvement in the dimensional stability of fir wood due to acetylation after 8 hours of soaking/drying procedure. At 20 % WPG (the level of acetylation reached with ACCOYA™) an impressive dimensional stability of 70 % is found. This means that wood modified to a WPG of 20 % will shrink and swell by about ¼ of the amount exhibited with unmodified wood, which is a significant improvement.

4.4. Effect of wood acetylation on mechanical properties

4.4.1. Static bending test

Data obtained from static bending tests were used in calculating three values: fiber stress at proportional limit (FS@PL), modulus of elasticity (MOE) and modulus of rupture (MOR). The mean values at air-dried (12% MC) condition of tested species were presented in table 6. The number of specimens for each treatment, minimum and maximum values, standard deviation and coefficient of variation (C.V %) are also given in those tables.

Table 6. Mean FS@PL at air-dried (12%MC) condition for each species

Species	Method	Number	FS@PL				
			Mean	Min	Max	S.D.	C.V
			N/mm^2	N/mm^2	N/mm^2	(%)	(%)
Hnaw	Control	10	49.7	34	55	6	10.6
	T1	10	54.6	42	61	5	
	T2	10	63.6	55	72	6	
Leza	Control	10	52	45	62	6	20.1
	T1	10	70	48	103	18	
	T2	10	73	45	85	14	
Pyinma	Control	10	49.5	44	55	4	16.9
	T1	10	54.7	43	81	10	
	T2	10	64.7	54	95	12	

From the tests, it can be seen that the mean FS@PL of non-acetylated Hnaw samples at 12% MC is 49.7 N/mm^2. That of acetylated samples was increased by 28%. It can also be found that the mean FS@PL of non-acetylated Leza samples at 12% MC is 52 N/mm^2 and that of acetylated samples is between 70 - 73 N/mm^2. Acetylation was increased by 40%.

The mean FS@PL of un-acetylated Pyinma samples at 12% MC is 49.5 N/mm^2. That of acetylated samples is 64.7 N/mm^2. FS@PL of acetylated Pyinma using Dipping treatment was increased by 10.5% and that using vacuum pressure treatment was increased by 30.7%.

According to the results, acetylation significantly affected the static bending strength. This result supported the reports of Hillis (1984). He found that bending strength and hardness of Scots pine increased by 15-20%.

Modulus of rupture (MOR)

Table 7. Mean MOR at air-dried (12%MC) condition for each species

Species	Method	Number	MOR				
			Mean	Min	Max	S.D.	C.V
			N/mm^2	N/mm^2	N/mm^2	(%)	(%)
Hnaw	Control	10	70.3	44	80	10	14.0
	T1	10	69.7	53	82	9	
	T2	10	103.0	79	118	14	
Leza	Control	10	65	54	79	9	19.6
	T1	10	97	71	126	19	
	T2	10	116	68	135	24	
Pyinma	Control	10	78.1	60	100	14	10.6
	T1	10	88.3	63	144	22	
	T2	10	103.8	88	128	15	

The average MOR of non-acetylated Hnaw samples at 12% MC is 70.3 Nmm^{-2}. After acetylation, it was found that 103 N/mm^2 by using vacuum – pressure treatment and 69.7 N/mm^2using dipping treatment. MOR of acetylated Leza samples by using vacuum pressure treatment increased by 46.5%. However, it was slightly decreased using dipping treatment.

The average MOR of non-acetylated Leza samples at 12% MC is 65 Nmm^{-2} and after acetylation, it was found of 116 N/mm^2 for vacuum pressure treatment and 97 N/mm^2 for dipping treatment. MOR of acetylated samples increased to 78.5% for vacuum pressure treatment and 49.2% for dipping treatment.

The average MOR of non-acetylated Pyinma samples at 12% MC is 78.1 Nmm^{-2} and after acetylation, it was found of 103 Nmm^{-2} by using vacuum pressure treatment and 88.3 N/mm^2 for dipping treatment. MOR of acetylated samples increased by 13% for dipping treatment and 19.8% for vacuum pressure treatment.

Modulus of elasticity (MOE)

Table 8. Mean of MOE at air-dried (12% MC) condition for each species

Species	Method	Number	MOE				
			Mean	Min	Max	S.D.	C.V
			N/mm^2	N/mm^2	N/mm^2	(%)	(%)
Hnaw	Control	10	10476	8929	13026	1532	11.3
		10	9350	6206	11231	1333	
		10	15368	12725	16513	1092	
Leza	Control	10	14185	9548	19441	3498	22.9
		10	7744	2930	12653	3435	
		10	16927	12040	18972	2455	
Pyinma	Control	10	12091	8829	14669	1905	13.9
		10	14402	12073	18477	1993	
		10	15047	12915	18858	1890	

According to the investigation carried out for this research, the average value of MOE with control and acetylated are given in Table (8). The average MOE of non-acetylated Hnaw samples at 12% MC is 10476 Nmm^{-2} and after acetylation, it increased to 15368 Nmm^{-2}. By acetylation treatment, MOE can be increased 46.7% for vacuum pressure treatment. For the Leza, the average MOE of non-acetylated samples at 12% MC is 14185 Nmm^{-2} and after acetylation, it increased to 16927 $Nmm^{-2,}$ about 20%. The average MOE of Pyinma was found to be 12091 Nmm^{-2}, after acetylation, it increased to 15047 Nmm^{-2} (24.4%).

Examination of the average values for three species showed significant difference between acetylated groups and their untreated samples. The values for acetylated wood samples were significantly increased. It appears that this property is affected significantly by acetylation for all tested species.

Tarkow *et al*. (1946) reported that the property changes were not significant, but there was some variation between species. Sitka spruce and basswood exhibited increases in strength and MOE upon acetylation to about 20%WPG, where as yellow birch showed a decrease in these properties at 16%WPG.

Larsson and Simonson (1994) studied the mechanical properties of acetylated *Pinus sylvestris* (pine) and *Picea abies* (spruce). The modulus of rupture (MOR) and modulus of elisticity (MOE) decreased by about 6 % for pine, but increased by about 7 % with spruce samples after acetylation.

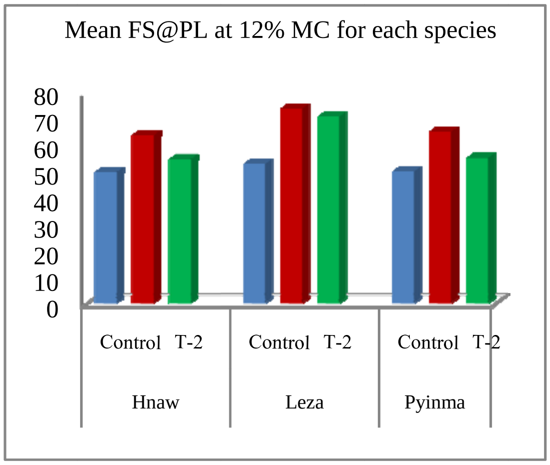

Figure 5.a

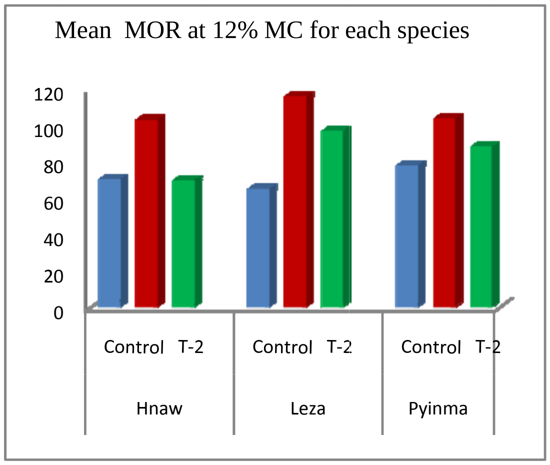

Figure 5.b

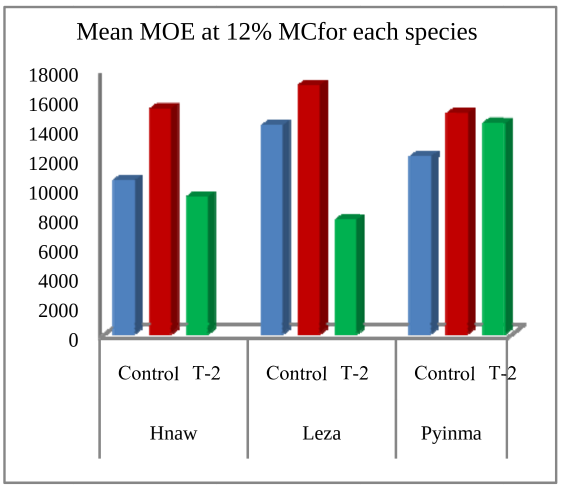

Figure 5.c

4.4.2. Compression parallel to grain test

Fiber Stress at Proportional Limit for each treatment of tested species at 12% moisture content are presented in table (9). The value of C. V. % for FS@PL can be high up to 24% (Anon, 1974).

Table 9. Mean FS@PL at air-dried (12%MC) condition for each species

Species	Treatment Method	No. of Samples	FS@PL (N/mm^2)				
			Mean	Min	Max	S. D	C.V. (%)
Hnaw	Control	10	31	21	40	6	18.2
	T1	10	34	22	38	7	
	T2	10	36	28	42	5	
Leza	Control	10	32	21	46	8	19.1
	T1	10	34	27	40	4	
	T2	10	38	26	49	8	
Pyinma	Control	10	35	30	40	4	17.4
	T1	10	28	22	35	4	
	T2	10	30	18	41	8	

The average FS@PL of non-acetylated Hnaw samples at 12% MC is 31 Nmm^{-2} and after acetylation, it was found that it increased to 34-36 N/mm^2. The average FS@PL of non-acetylated Leza samples at 12% MC is 32 Nmm^{-2} and after acetylation, it was found that it increased to 34-38 N/mm^2. The average FS@PL of the acetylated Hnaw and Leza samples were higher than the non-acetylated ones. The average FS@PL of non-acetylated Pyinma samples at 12% MC is 35 Nmm^{-2} and after acetylation, it was found that it decreased to 28 and 30 N/mm^2.

The coefficient values of FS@PL in compression parallel to grain at air-dried condition are lower than 24%. Thus, the results are presumed to be precise and reliable. The test of significance of the acetylation treatment was carried out by using Statistica software (One way ANOVA). The F' test indicates that it was not significantly different between treatments by acetylation. The ANOVA table is shown in Appendix (III).

Maximum crushing strength (MCS)

The average values of MCS for the tested species at 12% moisture content are given in table (10).

Table 10. Mean Maximum Crushing Strength at air-dried (12%MC) condition for each species

Species	Treatment Method	No. of Samples	MCS (N/mm^2)				
			Mean	Min	Max	S. D	C.V. (%)
Hnaw	Control	10	38	48	26	8	14.5
	T1	10	45	49	39	4	
	T2	10	39	45	28	5	
Leza	Control	10	36	51	24	8	14.9
	T1	10	39	44	33	4	
	T2	10	44	51	34	6	
Pyinma	Control	10	43	49	39	3	15.4
	T1	10	34	41	25	6	
	T2	10	34	44	21	7	

According to the investigations carried out for this study, it can be found that the average MCS of the acetylated Hnaw and Leza samples were 20% higher than the un-acetylated ones. This means that the strength can be increased by acetylation. This finding agreed with the results by Dreher (1964), he reported that the compressing strength increased by 6-36%.

However, as for Pyinma, it decreased slightly. The coefficient values of FS@PL in compression parallel to grain at air-dried condition are lower than 18%. Thus, the results can be precise and reliable. The test of significance was carried out by using F- test. The F-test indicates highly significant difference between treatments by acetylation at 95% confidence interval. It was found that acetylation affected this property significantly. The ANOVA table is shown in Appendix (IV).

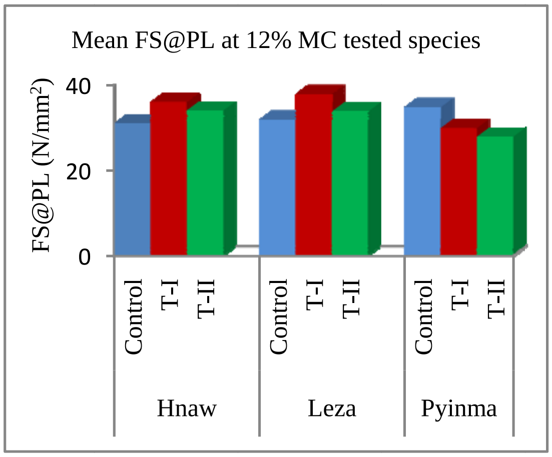

Fig. 6 (a)

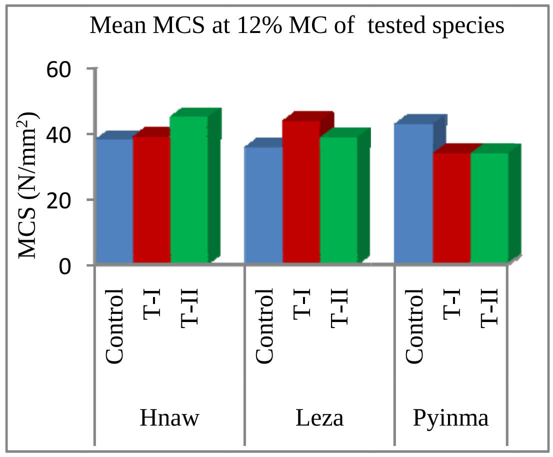

Fig.6(b)

4.4.3. Compression perpendicular to grain test

Fiber Stress at Proportional Limit

The fiber stress at proportional limit is the only value computed. The average values of FS@PL for the tested species at 12% moisture content are given in table (11). In this table, the number of specimens, maximum and minimum values, standard deviation (S.D), coefficient of variation (CV %), for each treatment of tested species are presented. The value of coefficient of variation for FS@PL can be high up to 28% (Anon, 1974).

Table 11. Mean FS@PL at air-dried (12%MC) condition for each species

Species	Treatment Method	No. of samples	FS@PL (N/mm^2)				C.V (%)
			Mean	Max	Min	S.D	
Hnaw	Control	10	10.67	12.08	9.34	0.86	10.4
	T1	10	11.25	15.87	9.93	1.70	
	T2	10	11.77	12.90	10.66	0.68	
Leza	Control	10	10.88	11.78	9.71	0.71	21.6
	T1	10	9.49	12.64	6.56	1.60	
	T2	10	9.49	11.14	7.89	1.11	
Pyinma	Control	10	11.14	13.63	6.42	2.46	12.0
	T1	10	9.08	11.23	7.65	1.14	
	T2	10	9.33	10.42	8.39	0.77	

According to this table, acetylated Hnaw samples showed higher strength than non-acetylated samples whereas acetylated Leza and Pyinma samples showed lower strength. The value of coefficient of variation of FS@PL in compression perpendicular to grain test at air-dried condition is lower than 28%. Thus the results can be précised and reliable. The analysis of variance was carried out by using F-test. The F- test indicates the significant difference between treatments by acetylation at 95% confidence interval. The ANOVA table is shown in Appendix (V).

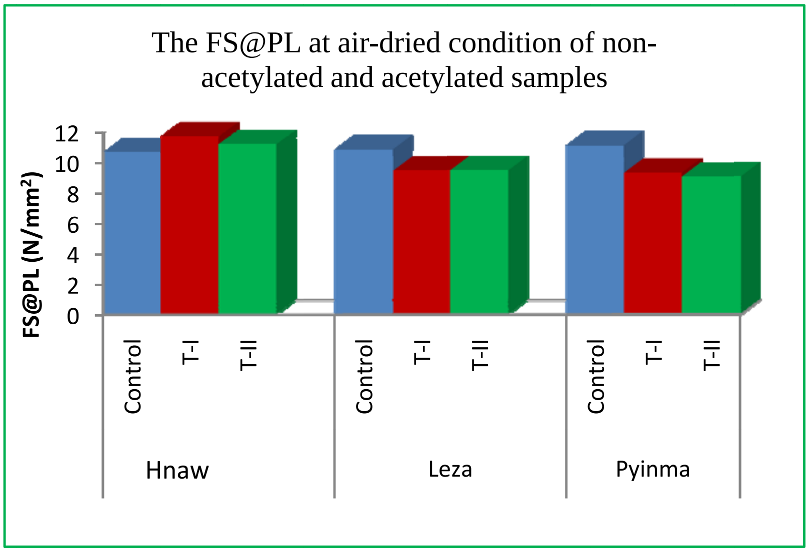

Fig. 7. The FS@PL at air-dried condition of non-acetylated and acetylated samples

4.4.4. Hardness Test

Mean values of Hardness tests for the tested samples at 12% moisture content are given in tables 12. In that table, the number of specimens, maximum and minimum values, standard deviation (S.D), coefficient of variation (C.V %), for each treatment of tested species are also presented. Mean values are presented for radial, tangential and end surfaces. The value of side hardness can be high up to 20% and the maximum coefficient of variation for end hardness is 10%, which can be high up to 17% (Anon, 1974).

Table 12. Mean values of Hardness the tested samples at 12%MC

Surface	Method	Hnaw			Leza			Pyinma		
		Mean N/mm^2	Dev N/mm^2	c.v (%)	Mean N/mm^2	Dev N/mm^2	c.v (%)	Mean N/mm^2	Dev N/mm^2	c.v (%)
Radial	Control	1667	289	9.2	1514	237	15.4	1485	447	14.0
	Vac/Pres	1559	226		1448	205		1194	220	
	Dipping	1679	269		1510	328		1282	186	
Tangential	Control	1347	251	11.2	1313	189	16.0	1379	427	22.4
	Vac/Pres	1364	238		1275	158		1057	276	
	Dipping	1444	226		1313	189		1116	215	
End	Control	3057	765	7.9	2335	255	12.4	2707	704	11.8
	Vac/Pres	2699	672		2223	258		1872	543	
	Dipping	2952	682		2210	317		2272	521	

According to this table, it can be seen that the non- acetylated samples of Hnaw is found to be slightly increased in radial and tangential surface but it decreased in end surface. In the case of Leza, the hardness of three surfaces remains unchanged in both non-acetylated and acetylated samples. As for Pyinma, the hardness of acetylated samples was lower than non-acetylated samples.

The analysis of variance was carried out by using F- test. The F- test indicates that there was no significant difference between treatments at 95% confidence interval. That is, acetylation may not affect the hardness of tested species.

These findings were different from the results of Dreher (1964), he showed that hardness increased by 22-31% by acetylation. Hillis (1984) also found that bending strength and hardness of Scots pine increased by 15-20%, which still was the case after a long- term exposure to high relative humidity. This in contrast to untreated pine of which the mechanical properties decrease when exposed to high relative humidity.

The chemically modified wood has fewer fibers per centimeter than non-modified wood. This means that if equal cross-sections of control and modified wood are used for mechanical tests, there will be fewer fibers to test in the modified wood as compared to the control. Since the cross-section of equal –sized control specimen contains about 10% more fibers than the modified specimen, the mechanical properties of the control should be higher than those of modified wood. Because of differences in volume and fibers per cross – section, it is difficult to compare properties between control and modified wood.

It should also be noted that the untreated wood contains more individual wood fibers than the acetylated wood of the same volume because the wood swells as a result of the presence of bonded acetyl groups in the cell wall, and a given cross-sectional area of modified wood would therefore contain fewer fibres. If account is taken of the increase in the cross-sectional area of a sample as a result of modification, then a sample exhibiting the same strength/stiffness before and after modification would appear to exhibit a reduction in these properties, which could then be falsely interpreted as degradation due to modification.

A study of the scientific literature gives a complicated picture with some workers reporting a slight increase in mechanical properties and some, a slight decrease. In comparing the properties of acetylated wood with the untreated controls, there are two competing effects influencing the mechanical properties of wood when it is acetylated. Acetylation of wood results in a decrease in equilibrium moisture content at a given relative humidity, which in turn yields a concomitant increase in tensile strength, MOR and MOE (Dinwoodie 2000). However, some degradation of the cell wall may also occur, due to the application of heat over extended periods and also due to the generation of acetic acid by-product in the cell wall. The extent of degradation will be strongly dependent upon the temperature and time of the modification reaction.

5. Conclusion

The following conclusions can be drawn from this study.

1) The shrinkage of acetylated Hnaw reduced 58% for tangential and 57% for radial than those of non-acetylated ones.
2) The shrinkage of acetylated Leza reduced 37% for tangential and 48% for radial than those of non-acetylated ones.
3) The shrinkage of acetylated Pyinma reduced 65% for tangential and 65% for radial than those of non-acetylated ones.
4) Maximum ASE (Anti-Swelling Efficiency) can reach up to 53% for Hnaw, 37% for Leza and 70% for Pyinma, by acetylation treatment after 24 hours soaking/drying procedure.
5) According to these findings, Dimensional Changes of acetylated Hnaw, Leza and Pyinma samples were significantly improved than those of non-acetylated samples.
6) According to static bending test, acetylated FS@PL can significantly improve 28% for Hnaw, 40% for Leza and 30% for Pyinma, respectively. For MOR, it can improve 32% for Hnaw, 17% for Leza and 15% for Pyinma. The MOE values of acetylated samples were also significantly different from those of non-acetylated ones.
7) In the case of compression parallel to grain test, both properties, FS@PL and MCS of acetylated Hnaw and Leza were higher than untreated one. Those of Pyinma decreased slightly.
8) There is no significant difference between acetylated and non-acetylated samples in compression perpendicular to grain test and hardness test for all tested species.
9) The results revealed that two properties, i.e. static bending and compression parallel to grain of the tested species were significantly improved by acetylation.

Therefore, it can be concluded that wood modification through acetylation can significantly enhance the wood properties of tested species.

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Appendix

Analysis of Variance for Static Bending Test (FS@PL)

Species	Source of Variation	df	SS	MS	F	Tabular F	C. V (%)
Hnaw	Treatment	2	997.816	498.908	14.228*	3.35	
	Error	27	946.732	35.064			
	Total	29	1944.548				
Leza	Treatment	2	2656.664	1328.332	7.691*		
	Error	27	4663.089	172.707			
	Total	29	7319.753				
Pyinma	Treatment	2	1180.010	590.005	6.484*	3.35	
	Error	27	2456.853	90.995			
	Total	29	3636.853				

Analysis of Variance for Static Bending Test (MOR)

	Source of Variation	df	SS	MS	F	Tabular F	C. V (%)
Hnaw	Treatment	2	7278.550	3639.275	28.155*	3.35	
	Error	27	3490.030	129.260			
	Total	29					
Leza	Treatment	2	13449.243	6724.622	20.198*	3.35	
	Error	27	8989.353	332.939			
	Total	29	22438.596				
Pyinma	Treatment	2	1180.010	590.005	6.484*	3.35	
	Error	27	2456.853	90.995			
	Total	29	3636.853				

Analysis of Variance for Static Bending Test (MOE)

	Source of Variation	df	SS	MS	F	Tabular F	C. V (%)
Hnaw	Treatment	2	204733361.40	7582717.09	4.596*	3.35	
	Error	27	47840760.42	1649681.39			
	Total	29	252574121.84				
Leza	Treatment	2	404606561.07	202303280.5	21.85*	3.35	
	Error	27	249977050.62	9258409.3			
	Total	29	654583611.68				
Pyinma	Treatment	2	48309464.88	24154732.44	6.49*	3.35	
	Error	27	100561064.49	3724483.87			
	Total	29	148870529.37				