Preservation and drying of commercial bamboo species of Vietnam

Dissertation

Zur Erlangung der Würde des Doktors der Naturwissenschaften
des Fachbereichs Biologie,
der Fakultät für Mathematik, Informatik und Naturwissenschaften
der Universität Hamburg

vorgelegt von
Thi Kim Hong Tang
aus Vietnam

Hamburg 2013

Genehmigt vom Fachbereich Biologie
der Fakultät für Mathematik, Informatik und Naturwissenschaften
an der Universität Hamburg
auf Antrag von Frau Professor Dr. E. MAGEL
Weiterer Gutachter der Dissertation:
Professor Dr. W. LIESE
Tag der Disputation: 25. September 2013

Hamburg, den 11. September 2013

Professor Dr. C. Lohr
Vorsitzender des
Fach-Promotionsausschusses Biologie

Acknowledgements

It was a great experience for me to pursue my PhD degree at the Centre of Wood Science, University Hamburg.

First of all, I would like to thank Prof. Elisabeth Magel for giving me the opportunity to fulfil my doctoral research and for her kind supervision.

My special thanks go to Prof. Walter Liese, who continuously supported me during my study. His extremely helpful scientific instructions kept me always in the right direction, so that I could finally reach my goal.

I deeply thank my advisors Prof. Olaf Schmidt, Dr. Johannes Welling, Prof. Dieter Eckstein, and Dr. Eckhard Melcher for their scientific guidance and technical assistance for my research. They gave me valuable suggestions and a great amount of knowledge.

To Dr. Uwe Schmitt, PD Dr. habil. Gerald Koch, Ms. Karin Brandt, Mr. Thomas Schwarz, Dongsheng Wei, Mr. Sergej Kaschuro, Ms. Stefanie Warsow, and all colleagues at the Thünen Institute of Wood Research and the Section Wood Biology, Centre of Wood Science, University Hamburg, I am very grateful to them for helping me to carry out my laboratory experiments as well as a great working environment.

My warm gratitude goes to Dr. Vu Thi Lam An, Ms. Nguyen Minh Hien, Ms. Ho Thuy Dung, Mr. Mac Van Cham, Nong Lam University of Ho Chi Minh City and the staff of the Bamboo Nature Company for their kind assistance during the field work. Without their support, it would not have been possible to conduct the extensive experiments.

I would like to give my thanks to the Government of Vietnam for granting me the scholarship to pursue my PhD degree. I also sincerely thank the Bamboo Nature Company, Duy Quy Company for providing me materials and facilities to fulfil the experiments.

Last but not least, I would like to thank all my family and my friends for encouraging me to pursue this research. Without their constant support, I would not have been able to finish this work.

Abstract

This research project dealt with three fields of treatment of the major commercial bamboo species of Vietnam: short-term protection of bamboo material against fungi, preservative treatment of bamboo culm parts by pressure, and kiln drying of bamboo culm parts.

The investigation on short-term protection of four species, *Bambusa stenostachya, B. procera*, *Dendrocalamus asper* and *Thyrsostachys siamensis,* was undertaken in the laboratory with small samples and in field tests with larger samples. The bamboos were treated with environment-friendly chemicals: acetic, boric, citric, formic, propionic, sorbic acid, and the salts potassium citrate, sodium acetate, sodium borate and sodium propionate. Among the 21 substances and mixtures tested, only acetic acid and propionic acid are effective against mould growth for an exposure period of at least eight weeks. For protection of *B. stenostachya* and *T. siamensis*, 10% acetic acid or 7% propionic acid is required, but for *B. procera* and *D. asper* 10% propionic acid is needed.

The preservative treatment of culm parts of three bamboo species, *B. stenostachya*, *D. asper* and *T. siamensis,* was investigated using various schedules with pressures of 2.5, 4, 5.5, 7 and 8.5 bar for 60, 90 and 120 minutes with two preservatives: a mixture of borax and boric acid (BB) and a mixture of sodium dichromate, copper sulphate and boric acid (CCB). The penetration and retention of the preservatives were evaluated for each schedule. For indoor use with 4 kg/m^3 BB, *T. siamensis* needs a pressure of 4 bar for 60 minutes, whereas for *B. stenostachya* and *D. asper* 5.5 bar and 60 minutes are required. For outdoor application with 10 kg/m^3 CCB, *T. siamensis* demands a pressure of 5.5 bar for 120 minutes, but *B. stenostachya* and *D. asper* need 7 bar for 60 and 120 minutes, respectively.

The investigation on kiln drying of the three bamboos, *B. stenostachya*, *D. asper* and *T. siamensis*, was done in a pilot-kiln with untreated culm parts and in industrial kilns for longer culm parts treated with boron. Four schedules with mild, relatively mild, severe and highly severe drying intensities were tested. The final moisture content, drying time and drying defects were determined. *B. stenostachya* dries moderately fast using a severe schedule with an initial temperature of 55 °C and a relative air humidity (RH) of 80% and a final temperature of 70 °C and 20% RH for 10 days. *D. asper* is difficult to dry and needs a relatively mild schedule with an initial temperature of 50 °C and a RH of 80% and a final temperature of 65 °C and RH of 20% for 13 days. *T. siamensis* is easy to dry applying a highly severe schedule with 65 °C at the initial stage and a RH of 80% and towards the end with 75 °C and 15% RH for 8 days.

Zusammenfassung

In dem Dissertationsprojekt wurde die industrielle Behandlung von Halmabschnitten wichtiger Bambusarten in Vietnam untersucht. Hierbei handelte es sich um den kurzfristigen Schutz gegen Schimmel, die Schutzbehandlung durch Kesseldruckimprägnierung und die Kammertrocknung von Halmabschnitten.

Der kurzfristige Schutz von *Bambusa stenostachya*, *B. procera*, *Dendrocalamus asper* und *Thyrsostachys siamensis* wurde mit kleinen Proben im Labor und mit langen Halmabschnitten im Feldversuch untersucht. Das Material wurde mit umweltfreundlichen Chemikalien getränkt: Essigsäure, Proprionsäure, Borsäure, Citronensäure, Ameisensäure, Sorbinsäure und die Salze Kaliumcitrate, Natriumacetate, Natriumborate und Natriumpropionate. Von den 21 Substanzen und Substanzmischungen sind Essigsäure und Proprionsäure für mindestens 8 Wochen wirksam gegen Verschimmeln. Die Schutzbehandlung von *B. stenostachya* und *T. siamensis* erfordert 10% Essigsäure oder 7% Proprionsäure, jedoch für *B. procera* und *D. asper* 10% Proprionsäure.

Die Tränkung von Halmabschnitten der Arten *B. stenostachya*, *D. asper* und *T. siamensis* mit Borax und Borsäure (BB) sowie Natriumdichromat, Kupfersulfat und Borsäure (CCB) wurde im Kesseldruckverfahren mit Drücken von 2.5, 4, 5.5, 7 und 8.5. bar für 60, 90 und 120 Minuten untersucht. Bestimmt wurden Eindringtiefe und Tränkmittelaufnahme. Die Aufnahme von 4 kg/m^3 BB zum Schutz unter Dach erfordert für *T. siamensis* 4 bar Druck für 60 Minuten, für *B. stenostachya* und *D. asper* 5.5 bar für 60 Minuten. Die Aufnahme von 10 kg/m^3 CCB zum Schutz von Bambus in der Außenverwendung erfordert für *T. siamensis* 5.5 bar für 120 Minuten, jedoch für *B. stenostachya* und *D. asper* 7 bar für 60 bzw. 120 Minuten.

Die Kammertrocknung ungetränkter Halmabschnitte von 1.4 m Länge erfolgte in einer Versuchskammer, während in einer industriellen Kammer die mit Borax und Borsäure getränkten Abschnitte von 2 und 2.2 m Länge getrocknet wurden. Mit den vier Trocknungsprogrammen "mild", "mäßig", "stark" und "sehr stark" wurden die Endfeuchte, Trocknungszeit und Trocknungsschäden ermittelt. *B. stenostachya* trocknet in zehn Tagen bei 55 ^oC Anfangstemperatur bei 80% relativer Luftfeuchte bis zur Endtemperatur von 70 ^oC bei 20% Luftfeuchte. *D. asper* ist schwieriger zu trocknen und benötigt 13 Tage unter moderaten Trockungsbedingungen von 50 ^oC Anfangstemperatur und 80% Luftfeuchte bis zur Endtemperatur von 65 ^oC mit 20% Luftfeuchte. *T. siamensis* ist in nur acht Tagen mit einem "sehr starken" Programm bei 65 ^oC Anfangstemperatur und 80% Luftfeuchte bis zur Endtemperatur von 75 ^oC und 15% Luftfeuchte zu trocknen.

Table of Contents

Abbreviations

AA	Acetic Acid
BA	Boric Acid
BB	Mixture of Borax and Boric Acid
CA	Citric Acid
CCA	Chromate Copper Arsenate
CCB	Mixture of Sodium Dichromate, Copper Sulphate and Boric Acid
EMC	Equilibrium Moisture Content
FA	Formic Acid
FMC	Final Moisture Content
FSP	Fibre Saturation Point
IMC	Initial Moisture Content
MC	Moisture Content
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
NA	Na-Acetate
NP	Na-Propionate
PA	Propionic Acid
RH	Relative Humidity
SA	Sorbic Acid
T	Temperature

List of Figures

List of Tables

1. INTRODUCTION

1.1 Bamboo resource in Vietnam

In the Global Forest Resources Assessment of FAO 2005, Vietnam belongs to the countries with the largest bamboo resource in the world (Lobovikov et al., 2005).Vietnam has about 1,400,000 hectares of natural bamboo forests with an estimated volume of 8.4 billion culms and around 150,000 hectares of bamboo plantations (Dinh et al., 2011). Furthermore, a number of companies have planted bamboo to supply their own bamboo reserves such as the Nature Bamboo Company, which has around 1,000 hectares of *Thyrsostachys siamensis* and *Dendrocalamus asper* in the Lam Dong province and 500 hectares of *T. siamensis* in the Binh Thuan province, and the Bamboo Grass Company with 200 ha of *T. siamensis* in the Lam Dong province (Le, 2010). In addition, a great number of bamboos are cultivated in almost all villages and gardens of rural households throughout the country.

In Vietnam, there are 194 bamboo species of 26 genera (Nguyen, 2006). The distribution of the bamboo is located mainly in the Central Highland, North Central Coast, Southeast and Northwest, consisting of the principal genera: *Bambusa, Dendrocalamus, Indosasa, Lingnania, Neohouzeaua, Phyllostachys, Schizostachyum, Sinocalamus* and *Thyrsostachys* (Nguyen, 2001). The economic species with large resources are *Bambusa balcoa, B. stenostachya*, *B. vulgaris, Dendrocalamus asper*, *D. barbatus*, *Indosasa angustata, Schizostachyum funghomii*, *S. pseudolima* and *Thyrsostachys siamensis*.

1.2 Usage of bamboo

Bamboo is the most valuable non-timber forest product and of pivotal support for the economy of Vietnam (Vu, 2004). In recent years, bamboo has become the main raw material for industrial manufacturing of furniture and houses for domestic and international markets. Bamboo culms are also widely exported.

In Vietnam, bamboo is available for a reasonable price. Consequently, it is used for many purposes ranging from the traditional utilization in rural areas up to industrial productions. Until now, the processing and utilization of bamboo still rely on traditional practices, mainly for housing and constructions, furniture making and interior decoration, agriculture implements as supporting sticks for crops planting and components for transport like simple rafts and boats.

Overall, about 100 companies are engaged in industries using bamboo in more than 700 craft villages with millions of labourers and produce commodities for domestic use and export (Phan, 2004). The bamboo industry includes the categories: handicraft, furniture, construction, bamboo-based panels, pulp for paper, and bamboo shoots.

Handicraft and furniture

Handicraft and furniture are a growing sector of the bamboo industry in the country. Vietnam has an enviable position as one of the world's leading centres for bamboo handicrafts and furniture. This industry is one of the country's key export revenue earners, generating $300 million every year. A report by the Mekong Development Program showed that since 2000 the export of bamboo products has increased by 15 to 25% each year. In 2007, bamboo exports reached an annual amount of $220 million, in 2009 that figure rose to $270 million, and 2010 to $350 million (Smith, 2010). Vietnam is the third largest exporter of bamboo after China and Indonesia (Hoogendoorn, 2012).

Bamboo furniture has been the leading product for export on a large scale. The bamboo furniture industry in Vietnam is mostly composed of cottage and small-scale manufacturers catering to local consumers. The medium and large firms generally provide for the foreign market. The country has 37 companies exporting bamboo furniture. Vietnamese bamboo companies currently have a strong presence on the international furniture market. Concerted efforts, however, must be directed towards overcoming considerable problems with the treatment of material as well as the original contemporary designs by the industry (Smith, 2010).

The specification of export products ranges from chairs, sofa sets and beds to kitchen cabinets and gazebos. They are wholly made of bamboo culm parts and splits, which must often be treated to ensure their quality. Most of the manufacturers prefer culm parts without skin. The general process of bamboo furniture production is shown in Fig. 1.1.

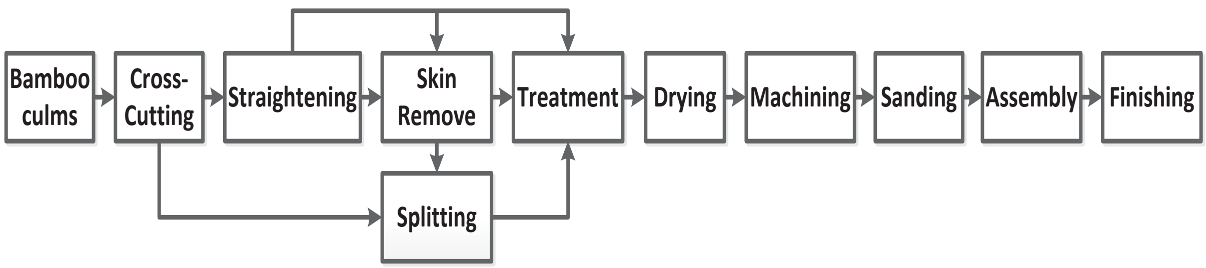

Fig. 1.1. General process of bamboo furniture production

For making handicraft and furniture mainly the bamboos *Dendrocalamus asper*, *D. barbatus, Thyrsostachys siamensis* from plantations and *Bambusa balcoa*, *B. stenostachya* from natural forest are used.

Construction

Bamboo houses have traditionally been built in the rural areas of Vietnam since a long time. Recently, several bamboo buildings have been created for the national tourism service such as houses in resorts and bamboo-based restaurants. They have also been exported in a notable quantity. For housing, some species with thick culm walls are preferred such as *Bambusa stenostachya*, *Dendrocalamus asper*, *D. barbatus* and *Thyrsostachys siamensis* (Do, 2006).

Bamboo-based panels

Five factories in North Vietnam use bamboo to produce various panels with a capacity ranging from 15,000 to 130,000 tons of products per year (Vu, 2004). The processing of bamboo-based panels is mainly done with *Dendrocalamus barbatus* from plantations.

Pulp and paper

Bamboo is an important source for pulp and paper in Vietnam. For the paper industry, some species like *Bambusa balcoa, Schizostachyum pseudolima* and *Bambusa procera* from natural stands are the major material (Ha, 2004). For the whole country, the paper industry consumes approximately 150,000 – 180,000 tons of culms per year (Vu and Le, 2005).

Bamboo shoots

Besides the useful culms, bamboo shoots supply food for domestic consumption and export. As major species, *Bambusa oldhamii* and *Dendrocalamus latiflorus* are used for shoot production.
Furthermore, bamboo is also widely exported as culms in large quantities.

1.3 Properties of bamboo in view of its utilization

1.3.1 Introduction to the species studied

The study concentrated on *Bambusa stenostachya* Hackel, *Dendrocalamus asper* Backer, and *Thyrsostachys siamensis* Gamble, which are the commonly used species, widely spread throughout the country and sufficiently available. Furthermore, they are mainly needed for construction and manufacturing furniture in the bamboo industry of Vietnam.

1.3.1.1 *Bambusa stenostachya*

Bambusa stenostachya with its local name "Tre Gai" is one of the most popular bamboo species of Vietnam distributed notably in natural stands of the provinces Quang Nam and Quang Ngai, Central South Vietnam, and widely planted through the country (Dinh et al., 2011). This species is principally used for constructions and outdoor furniture. Many firms in South Vietnam, such as the Bamboo Hardwood Company, Bamboo Living Co., and Bamboo Nature Co., use the culms for housing and furniture for exportation.

The sympodial clump is usually large and umbrella-shaped. The culms are about 15 - 28 m tall and slightly irregular (Fig. 1.2). The internodes are 20 - 30 cm long with a diameter of 6 - 14 cm, and the thickness of the culm wall ranges from 10 - 18 mm (Nguyen, 2006). Branches are borne from lower nodes upwards and alternately arranged along the culm. The middle branches are dominant and together with small branches form a gigantic fan-like structure.

Fig. 1.2. Culms of *Bambusa stenostachya*

1.3.1.2 *Dendrocalamus asper*

Dendrocalamus asper with its local names "Manh Tong" is widely planted in Southeast Vietnam and in some provinces of the Mekong Delta with large areas of about 10,000 ha (Do, 2010). This species is valued in Vietnam for the production of edible shoots as well as culms, which supply the material for buildings, furniture and structural items. Recently, several bamboo manufacturers in South Vietnam, like the Bamboo Nature Co., Cam Bamboo Co., and Vina Wood Co., preferably use these culms for their products.

The culms of the sympodial bamboo are densely tufted, about 20 - 30 m tall and relatively straight (Fig. 1.3). At their base, they are covered with fine, white, golden-brown hairs, giving them a velvet-like appearance when young, but becoming dark green when old. The internodes are 20 - 45 cm long with a large diameter of 8 - 20 cm; the culm walls are relatively thick of 11 - 20 mm but become thinner towards the top of the culm.

Fig. 1.3. Culms of *Dendrocalamus asper*

1.3.1.3 *Thyrsostachys siamensis*

Thyrsostachys siamensis with its local name "Tam Vong" is one of the most common bamboo species growing mainly as a forest. It is also largely cultivated in the provinces Binh Thuan, Binh Duong, Lam Dong and Tay Ninh with around 15,000 ha plantation (Do, 2010). The culms are the main raw material of the Bamboo Nature Co., Bamboo Grass Co., and many other companies in South Vietnam for furniture for exportation.

The sympodial clump is medium sized of 5 - 10 m. The culms are about 10 - 15 m tall and relatively straight. The internodes are 12 - 30 cm long with a small diameter of 32 - 50 mm and almost solid at the bottom (Fig. 1.4), but hollow from the middle towards the top. The lower nodes are covered with a circle of rootlets and when young with fine, golden-brown hairs.

Fig. 1.4. Culms of *Thyrsostachys siamensis*

1.3.2 Anatomical structure of the culm

The anatomical features affect the physical and mechanical properties of a culm, and should be taken into account in regard to the choice of seasoning, preservation, and final application.

Morphology

The properties of a bamboo culm are determined by its anatomical structure. The culm is characterized by nodes and internodes. The nodes provide the transversal interconnection with their solid cross wall, called diaphragm. The internodes have a culm wall, surrounding a large cavity, called lacuna. A few bamboo species have solid internodes mainly at the bottom part, like *Dendrocalamus strictus*, *Dinochloa* spp. and *Thyrsostachys siamensis* (Liese, 1998).

The cross section of a culm internode is structured by outer and inner layers with parenchyma tissue and vascular bundles in between. The cortex, called skin, forms the outer part of the culm. The skin thickness of the three bamboos studied by microscopy is 0.02 - 0.13 mm and varies with the species (Fig. 1.5). The main function of the cortex is the protection against mechanical damage and water loss. The radial movement of water for the drying as well as for the penetration of preservatives is hindered by the skin. Consequently, the preservative treatment as well as the drying is more difficult than for culm parts without a skin which is often removed for furniture making.

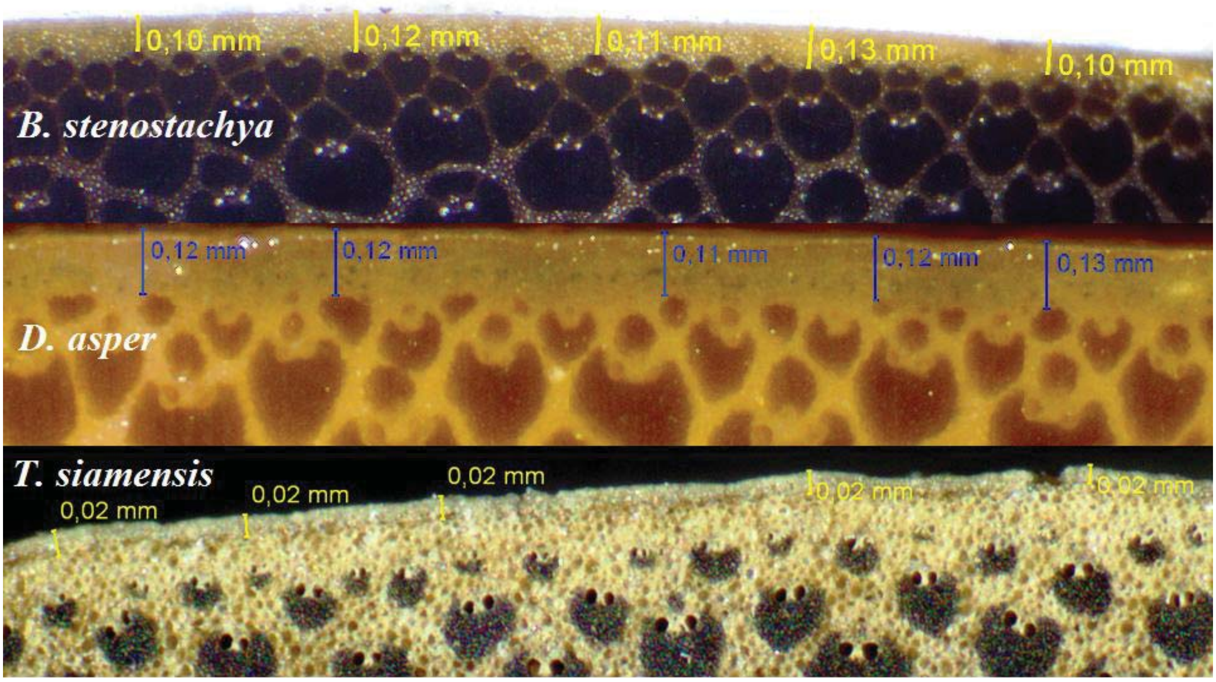

Fig. 1.5. Cortex thickness of three bamboos *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*

The diameter and wall thickness decrease gradually with the height of the culm, whereas the length of internodes increases (Table 1.1). This character partly influences the drying rate and treatability of the bamboo culm (Kumar et al., 1994; Rehman and Ishaq, 1947).

Table 1.1. Culm features of three bamboo species studied

Species	*Bambusa stenostachya*			*Dendrocalamus asper*			*Thyrsostachys siamensis*		
Position	B	M	T	B	M	T	B	M	T
Diameter (mm)	80-105	75-88	22-30	85-140	78-90	27-35	40-60	25-35	8-10
Wall thickness (mm)	14-20	8-10	2-5	12-18	10-14	4-6	solid	8-12	2-4
Internode length (cm)	12-18	20-36	30-35	20-28	25-32	38-45	12-18	20-25	28-35

B: Bottom; M: Middle; T: Top (Hoang and Tang, 2007)

Microscopic anatomy

The culm comprises about 50% parenchyma cells, 40% fibres, and 10% conducting tissue, arranged in vascular bundles (Liese, 1998). The ground tissue of parenchyma cells stores the energy as sugar and starch. The fibres are the strength components in the vascular bundles and arranged in sheaths and bundles around the vessels as conducting cells. The vascular bundles at the outer part of the culm are smaller, denser and more dispersed than towards the inner part (Grosser and Liese, 1971). This feature is shown in detail for the three bamboos investigated in Fig. 1.6.

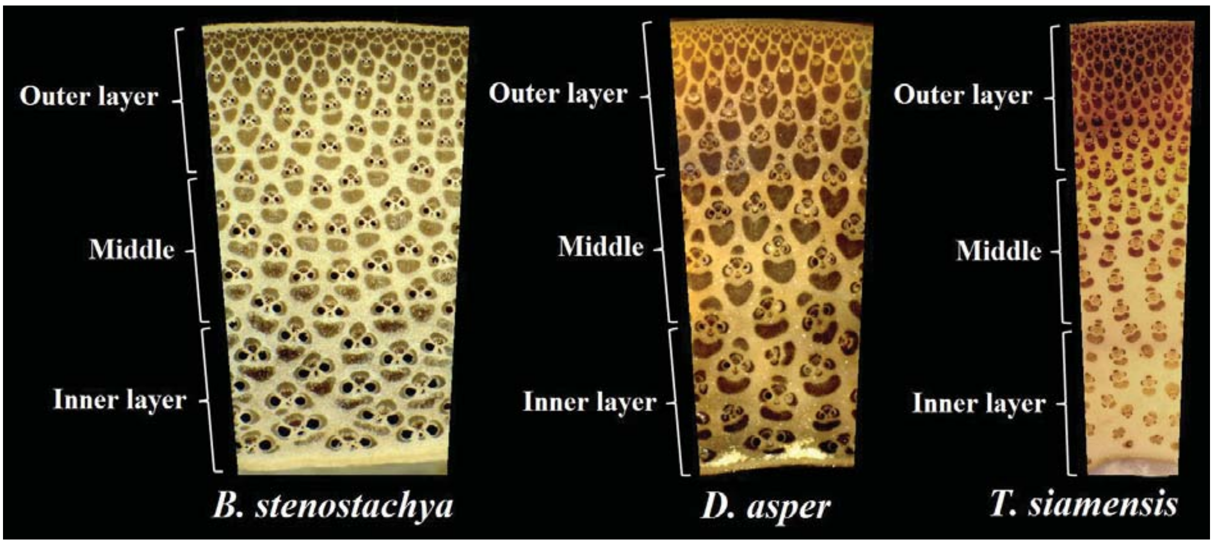

Fig. 1.6. Culm structure of three bamboos as cross-section

According to the classification of the four basic vascular bundle types of a bamboo culm by Liese and Grosser (2000), *B. stenostachya* and *D. asper* have vascular bundle type IV, which consists of the central vascular strand with small sclerenchyma sheaths and two isolated fibre bundles on the opposite side. *T. siamensis* is categorised under type III, consisting of two parts, the central vascular strand with sclerenchyma sheaths and an additional separate fibre strand located at the protoxylem side.

The outer layer provides most of its strength, whereas the inner part stores nutrients and starch in the parenchyma and is consequently liable to attacks by beetles and blue stain fungi. Unlike wood, bamboo has radial cells only in the nodes and thus lateral movement of liquids is restricted (Liese, 1998).

1.3.3 Physical and mechanical properties

Density

The density of bamboo varies from about 0.4 - 0.9 g/cm^3, depending on the anatomical structure such as the quantity and distribution of fibres around the vascular bundles (Zhou, 1981; Abd. Razak et al., 1995; Qisheng et al., 2002). Accordingly, it increases from the inner layer to the outer part of the culm and along the culm from the bottom to the top (Liese, 1985; Nordahlia et al., 2012). These factors also apply to the investigated *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis* (Table 1.2).

Table 1.2. Density of three bamboo species studied

Species	*Bambusa stenostachya*			*Dendrocalamus asper*			*Thyrsostachys siamensis*		
Position	B	M	T	B	M	T	B	M	T
Density (g/cm^3)	0.65	0.72	0.81	0.71	0.78	0.89	0.41	0.46	0.62

B: Bottom; M: Middle; T: Top (Hoang and Tang, 2007)

The density influences the preservative treatment and the drying of bamboo. Generally, bamboo with a higher density is more difficultly to treat and dry than with a lower one (Laxamana, 1985).

Moisture content

The moisture content of the bamboo culm and its products influences the dimensional stability of the bamboo material and is thus often associated with its toughness, density, strength, working properties, and durability (Liese, 1985).

The moisture content can be expressed as percentage of either dry or wet weight. For most purposes, the moisture content is based on the oven-dry weight. Moisture content on dry and wet basis is defined as follows:

$$\text{Moisture content (MC\%)} = \frac{\text{Wet weight - Dry weight}}{\text{Dry weight}} \times 100$$

The moisture varies within and between the species, season of felling, height and age of the culm, as shown in several studies, e.g., by Rehman and Ishaq (1947), Liese and Grover (1961), Sharma et al. (1972), Espiloy (1992), Abd. Latif and Zin (1992), Abd. Latif and Liese (1995). Green bamboo may have up to 150% moisture.

The moisture content is also relevant for the preservative treatment as well as for drying of the bamboo culms. The moisture content must be taken into consideration when choosing a suitable preservative and method as well as a proper treatment schedule.

Equilibrium moisture content

As hygroscopic material, bamboo absorbs or loses moisture until the amount is in balance with the surrounding atmosphere. The amount of moisture at this point of balance is called the equilibrium moisture content (EMC). The EMC depends mainly on the relative humidity and temperature of the surrounding air.

Many studies on physical properties (Sulthoni, 1989; Sattar et al., 1994; Hamdan et al., 2007; De Vos, 2010) showed that the EMC of bamboo is very similar to wood. Thus, the computed data of wood relation between EMC and temperature and relative humidity could be used for the bamboo-moisture relationship.

The EMC is an important service factor and especially applied for drying. Kiln drying usually requires controlled EMC conditions, namely temperature and relative humidity.

Fibre saturation point

The fibre saturation point (FSP) is defined as the moisture content at which the cell walls are saturated without any water in the cell cavities. In bamboo, the FSP is influenced by the composition of the tissue and the amount of chemical constituents (Liese, 1985).

The mean FSP of bamboo in general is around 17 - 25% (Ota, 1955; Kishen et al., 1958; Sharma, 1988; Hamdan et al., 2007). For *Bambusa stenostachya* it is 21%, for *Dendrocalamus asper* 25%, and for *Thyrsostachys siamensis* 24% (Nguyen, 2005; Bui, 2006; Ho, 2011).

Shrinkage

Shrinkage of bamboo is the basic cause of many problems that occur during culm drying and during its service. Unlike wood, shrinkage starts in both cell-wall thickness and cell diameter as soon as moisture begins to decrease. This is due to the high amount of parenchyma cells, which lose their moisture first. Shrinkage starts simultaneously with the decrease of moisture content but does not continue regularly. As water content diminishes from 70 to 40%, shrinkage stops; below this range, it will be initiated again. Parenchyma tissue shrinks less in bamboo than in timber, while vascular fibres shrink as much as in timber of the same specific gravity (Liese, 1985).

Bamboo tissue shrinks mainly in the radial and tangential direction. The radial and tangential shrinkages decrease with the height of the culm since the top portion has a higher number of vascular bundles (Liese, 1998). For the three bamboos studied this characteristic is shown in Table 1.3 by Vo (2007), Pham (2009) and Ho (2011).

Table 1.3. Shrinkage of three bamboo species studied

Species	Shrinkage (%) from green to oven-dry moisture content					
	Tangential			Radial		
	Bottom	Middle	Top	Bottom	Middle	Top
Bambusa stenostachya	8.4	7.5	7.1	8.2	6.9	6.3
Dendrocalamus asper	7.5	6.3	5.6	6.8	5.6	5.1
Thyrsostachys siamensis	9.7	7.5	6.9	10.9	8.2	7.4

(Vo, 2007; Pham, 2009; Ho, 2011)

Mechanical properties

The strength of bamboo generally increases by the thickening of the fibre walls until maturity of about three years, but also later on (Liese, 1987). The selection of suitable bamboo species and age in addition to other related factors, such as site and season, influencing the strength properties, is of utmost importance.

The variation in density within a culm and between species has a major effect on the strength (Espiloy, 1985; Janssen, 1985; Anwar et al., 2005). The mechanical properties of *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis* are presented in Table 1.4.

Table 1.4. Strength properties of three bamboo species studied

Properties	*Bambusa stenostachya*	*Dendrocalamus asper*	*Thyrsostachys siamensis*
Compression strength (MPa)	82.4	86.5	43.7
MOE (MPa)	9895	10810	6575
MOR (MPa)	138	152	68

MOE: Modulus of elasticity; MOR: Modulus of rupture (Hoang and Tang, 2007)

1.3.4 Chemical composition of the culm

The chemical composition of bamboo should be considered since it influences the biological durability. Table 1.5 presents the major constituents of the three bamboos investigated.

Table 1.5. Chemical composition of three bamboo species studied

Chemical composition (%)	Species		
	Bambusa stenostachya	*Dendrocalamus asper*	*Thyrsostachys siamensis*
Holocellulose	66.3	68.2	63.8
Lignin	25.8	22.5	29.2
Ash	3.1	1.8	3.9
Cold water solubility	6.4	7.8	7.1
Hot water solubility	7.2	9.9	8.9
1% NaOH solubility	25.6	24.2	27.8
Alcohol-benzene solubility	5.8	4.2	6.9

(Nguyen, 2005; Bui, 2006; Ho, 2011)

The chemical composition of bamboo is similar to those of hardwoods, except for the higher alkaline extract, solubility in water, ash and silica content (Tomalang et al., 1980; Liese and Kumar, 2003). The high solubility contents in both hot and cold water may influence the natural durability of the material (Purusotham et al., 1953; Abd. Latif and Liese, 1995; Denrungruang, 2004). Carbohydrates in a bamboo culm are easily degraded by mould and decay fungi and favour insect attack.

1.3.5 Durability

1.3.5.1 Agents of deterioration

Bamboo can be degraded by abiotic and biotic agents.

Abiotic deterioration

Deterioration occurs as splits or cracks, opening the inside of a culm to moisture as well as to invading beetles and fungi. Cracks arise mainly when the bamboo culm has been cut at a young stage or has not been properly seasoned (Laxamana, 1985). In addition, bamboo is a hygroscopic material; thus, it will shrink when it dries and swells when wetted, which can also induce splits and checks (Wang, 1972).

Weathering of exposed surfaces is a complex phenomenon due to exposure to ultra-violet light, heating and cooling, wetting and drying, leading to bleaching, and eventually surface checks. Weathering itself hardly changes the bamboo significantly. By the action of microorganisms and the presence of algae under moist conditions, its appearance will change.

Biotic deterioration

The culm tissue does not contain phytotoxic substances as compared to the heartwood of many tree species, whereas its parenchyma cells comprise a large amount of starch. Consequently, bamboo is liable to be attacked by fungi and insects, such as beetles and termites, as it has a low resistance to such organisms (Liese et al., 2002).

Fungi

Fungi invade bamboo only with sufficient moisture content, at least above the fibre saturation point of 20 - 22%; thus, dried bamboo is protected against fungal degradation (Mohanan, 1997; Liese and Kumar, 2003). Moisture content may be high in processed culms, when they have been either insufficiently seasoned or improperly stored. Water uptake occurs easily through the cut ends with their wide metaxylem vessels and to a much lesser extent through the sheath scars at the nodes. Vessel blocking through slime and tyloses following air penetration can retard moisture penetration but cannot prevent it. Lateral uptake through the outer waxy epidermis is very little but easier through the inner culm layer (Liese, 1998).

Beetles

Bamboo culms as well as bamboo products are very vulnerable to powder post beetles, mostly *Dinoderus brevis*, *D. celluris, D. minutus* and *Lyctus* spp. The attack is related to the presence of starch in the parenchyma and may start as soon as the culm is felled. Bamboos are more rapidly destroyed when harvested during summer than when felled after the rainy period as the latter has less starch (Plank, 1951; Liese, 1988).

Termites

Termites are the most aggressive organisms to wood and bamboo. As social insects, they 1ive in large colonies. They are among the few insects capable of utilizing cellulose as a source of food. Their attack leads to a rapid deterioration, whereby only a thin outer layer of the bamboo often remains. Termites are hardly influenced by the starch content (Liese and Kumar, 2003; Remadevi et al., 2005).

1.3.5.2 Natural durability

Bamboo in an endangered environment is susceptible to degradation by similar organisms which attack wood (Kleist et al., 2002; Razak et al., 2006; Suprapti, 2010; Ma et al., 2010; Kim et al., 2011; Schmidt et al., 2011; Wei et al., 2012). Moreover, bamboo is more likely to biodeteriorate due to its large starch content.

The service life of bamboo structures is determined considerably by the rate of biological degradation. Generally, the natural durability of bamboo is very low and influenced by species, environmental conditions, and nature of use. Untreated bamboo has an average life of less than one year when exposed outside and in soil contact. Under cover, it may last 4 - 5 years and much longer under favourable conditions (Liese and Kumar, 2003).

Split bamboo with its easier access to the parenchyma is more rapidly destroyed than culms. The bottom part of a culm has a higher durability than the middle and top portion, and the inner part of the culm is easier attacked than the outer one (Sulthoni, 1996; Liese and Kumar, 2003; Schmidt et al., 2011).

In tropical humid areas, enormous quantities of bamboo culms stored in forest depots and mill yards decay and deteriorate. The severity of decay and biodeterioration depends on the duration of storage, bamboo species, and environmental and storage conditions. During storage up to 12 months, about 25 - 40% damage of culms has been reported in Vietnam (Nguyen, 2002). Degradation of bamboo materials by fungi is a serious problem for Vietnamese bamboo factories in storage, during processing and overseas transport of bamboo culms (Fig. 1.7 and Fig. 1.8).

Therefore, a prevention of decay during storage of bamboo material and a prolongation of the service life of bamboo structures are needed to enhance the value of the bamboo products.

Fig. 1.7. Moulded bamboo culm parts at arrival in Hamburg after shipping from Vietnam

a) b)

c)

Fig. 1.8. Moulded bamboo materials at a Bamboo factory in Vietnam

a) Moulded fresh culms during storage; b) Surface of a table infected by moulds;
c) Moulded culm parts after processing

2. STATE OF ART

2.1 Bamboo preservation and drying in Vietnam

2.1.1 Preservation

For bamboo preservation, non-chemical and chemical methods are applied to protect culm tissue against biological agents of deterioration.

2.1.1.1 Non-chemical methods

In rural areas of Vietnam, several non-chemical methods for bamboo protection are applied. They can be carried out by untrained villagers with simple equipment and little cost. Some of these traditional methods considerably increase the resistance against fungal and insect attack.

Reduction of starch content

In bamboo culms, the carbohydrates (starch and sugars) are the principal nutrients for fungi and insects. Methods commonly used for lowering their content are:

- *Harvesting of bamboo during the low-sugar content season*

The sugar content in the culm varies with the seasons. During the growing season, the culm reduces its carbohydrates in the parenchyma to provide building material for the expanding shoots. Thus, the carbohydrates are reduced (Magel et al., 2006). Therefore, the culms are harvested during the following dry season: in South Vietnam from November to March and in North Vietnam from August to December.

- *Curing*

The bamboo culms are cut at the bottom and left for some time with branches and leaves at the clump. As respiration of the tissues still goes on, the starch and sugar content in the culm are decreased. Thus, the infection by borers is reduced, but there is no effect on the attack by termites and less by fungi.

- *Water-logging*

Water-logging is commonly applied in Vietnam as in many Asian countries. Fresh bamboo culms are soaked in running or stagnant water for 1 - 3 months. This process is said to leach out carbohydrates thus resulting in an enhanced resistance of the culm. In fact, during the water-storage the starch content is reduced partly by bacterial action. The method might therefore improve the resistance against borers but not against termites and fungi (Sulthoni, 1988; Nguyen, 2002). Submergence in water may lead to staining and bad odour of the culms.

Water-logging is still used for treating bamboo materials for making handicraft and furniture in many traditional craft villages of North Vietnam as well as generally for housing in rural areas.

Lime-painting

Bamboo culms and bamboo mats for housing are painted with slaked lime. Besides the ornamental effect of the white colour, a prolongation of service life is expected as a side effect. The surface becomes alkaline, which is assumed to inhibit fungi. However, some tests in the present work have shown that lime-painting of bamboo could not inhibit fungal growth. Chemicals with an alkaline pH-value were also shown to be ineffective during the experiments on short-term protection (see Publication 1). Lime-painting is applied in rural areas and is thought to have some protective effects.

Smoking

The culms are stored inside a house above a fireplace for some time, so that the ascending smoke causes a blackening of the culm. Toxic agents may be produced, which lead to some resistance.

For the production of bamboo furniture in some companies in North Vietnam, the culms are heated by a blowtorch, so that they become yellow-brownish. This may provide some resistance against beetle attack. For constructional dimensions, however, cracks can occur, which may lead to an easier attack (Nguyen, 2002).

Although the non-chemical methods have been used for a long time in the villages of Vietnam, not much is known about their real effectiveness. Therefore, more information about these methods has to be collected and special investigations undertaken.

2.1.1.2 Chemical methods

Treatment with chemicals for bamboo preservation is more effective than any non-chemical method and ensures a longer life for their structures. The preservation can be performed with various chemicals, depending on the goals.

Preservatives

In Vietnam, preservatives commonly applied for bamboo protection are:

Boron is most widely used for treatment of rubber timber and also employed for bamboo in South Vietnam and at some places in North Vietnam. The preservative is marketed under names like CELBOR by Celcure Group, Malaysia, and TIMBOR by Preservation Resource Group, USA. A preservative XM5 containing Cu-sulphate and $K_2Cr_2O_7$ is used in North Vietnam.

Other chemicals, such as sodium fluoride and creosote have rarely been applied. In recent years, the CCB (mixture of Sodium Dichromate, Copper Sulphate and Boric Acid) has been taken for treatment of rubber timber, but not yet for bamboo preservation. The CCA (Chromate Copper Arsenate) has never been used and is nowadays prohibited.

Pentachlorophenol was used a preservative in Vietnam mainly for the temporary protection of bamboo against fungi and insects. However, due to its poisonous effect, pentachlorophenol has been banned in Vietnam and partly in the world.

Recently, a few chemical companies have been marketing products such as “Celbrite TC” (Anti-Sapstain) by Celcure Group of Companies, “SARPECO 8” containing dithiocarbamate, propiconazole, tebuconazole and cypermethrine by SARPAP, China and “EVOTEK 230 SE”, composed of prochloraz and carbendazim by LANXESS, Germany. However, these preservatives have not been used yet in Vietnam since bamboo companies are fearful of the high cost, environmental effects and about the real efficiency against fungi and insects.

Treatment methods

- *Treatability of bamboo culms*

The anatomical structure of the bamboo culm determines its treatability and the methods applied. The main pathways for penetration as well as for releasing moisture are the metaxylem vessels. The pathways are mainly the cross ends of a culm and to a small extent the cut branches at the nodes. The radial passage is only by diffusion because no ray cells exist (Liese, 1998). Generally, the anatomical structure of the bamboo culm makes treatment with preservatives as well as drying more difficult than for wood (Laxamana, 1985; Liese and Kumar, 2003; Lahiry, 2005).

There are several methods for impregnating bamboo with preservatives. In Vietnam, the following are commonly applied:

- *Steeping or butt-end treatment*

Freshly cut culms with their branches and leaves are placed upright in a container, usually a plastic bucket with 8% boron solution or 15% XM5. The butt-end is kept immersed up to about 25 cm. Due to the ongoing transpiration by the leaves, the uptake of the preservative by the vessels is accelerated. The treatment time takes 8 - 14 days, depending on the freshness and the length of the culm.

The steeping or butt-end treatment is commonly applied to fresh culms for agriculture crops.

- *Soaking*

The open-tank treatment by soaking fresh and dried culms and splits is a rather simple method that leads to a protective effect. The materials are prepared to size, and soaked in a solution of 7% boron or 10% XM5. The treatment time takes about 2 - 3 days for splits and 7 - 9 days for culm parts. For culm parts with skin, the solution penetrates by diffusion mainly into the ends, partly at the nodes and to a small extent through the outer culm wall. Culm parts without skin as well as splits can be treated easier than round bamboo.

The soaking method is commonly applied in rural areas of North Vietnam for culms and splits to be used for making handicraft and furniture.

- *"Vietnam method"*

The "Vietnam method" is a speciality of bamboo treatment. The method is applied for fresh bamboo culms. Its principle is the use of the upper internode as a reservoir for the treatment solution. Its inner wall is either scraped at a depth of 1-2 mm or by a round incision with a sharp tool to disrupt the inner terminal layer. The cavity is filled up daily with the preservative solution, which diffuses into the parenchyma tissue, fibres and especially the vessels located in the inner part of the culm wall, where it flows down by gravity. Therefore, this method is also called in Vietnam "gravity method". The foot of the culm is put into a plastic bucket to collect the liquid coming out. The treatment is completed, when the liquid at the culm foot has the same colour as the initial solution.

The treatment time depends on the length and freshness of the culm as well as on the concentration of the solution. The treatment of *Dendrocalamus barbatus* culm parts of 3 m long with the chemical XM5 needs about 40 hours. Culm parts with a moisture content of less than 50% could not sufficiently take up the treatment solution (Nguyen, 2002).

The same principle has been used for the Vertical Soak and Diffusion method developed by the Environmental Bamboo Foundation (EBF), Bali, Indonesia. The standardized treatment process is called “Vertical Soak and Diffusion (VSD)” system (EBF, 2003). This method does not use only the lacuna of the upper internode, but the whole culm serves as a reservoir for the solution as all diaphragms are fractured with a sharpened stick, except the lowest. The lacuna of the internodes is filled up with a borax/boric acid solution and refilled daily. The solution diffuses into the inner culm, containing the carbohydrates. After about two weeks the lowest diaphragm is punctured and the solution collected for further use.

- *Pressure method*

The pressure method is mainly used for the treatment of dried bamboo. The principle of the process is to force the preservative solution into the bamboo tissue. This can be done by a vacuum and/or by increasing the pressure upon the preservative in the treatment cylinder.

In Vietnam, the pressure method is mainly applied for bamboo culm parts and splits for making furniture and housing for export. Culm parts and splits are treated with 7% boron or 8% XM5 with a pressure of 7 kg/cm^2 for 2 - 3 hours. This schedule is mostly applied for all bamboo species. However, the pressure treatment should be conducted according to the properties of the bamboo species. Therefore, it is necessary to evaluate the proper treatment of bamboo species used, which is the goal of the present experimental work.

2.1.2 Drying

Importance of bamboo drying

The drying of bamboo before use is necessary since dry bamboo is stronger and less susceptible to biological degradation than moist bamboo. Furthermore, shrinkage and swelling are directly related to the moisture content. Moist bamboo affects the processing, such as machining, gluing and painting. Greater dimensional changes would ultimately occur if the bamboo has not been dried before being used. The bamboo should be dried to the equilibrium moisture content corresponding to the service conditions before the manufacturing process. Superior bamboo products require a final moisture content between 8 and 12%.

Commonly, seasoning bamboo in Vietnam is done with air-drying or kiln drying.

Air-drying

In Vietnam, air-drying has traditionally been used for a long time in rural areas and in bamboo factories with small capacities.

Air-drying is the process of removing moisture from bamboo by exposure to atmospheric conditions. There are two types, the horizontal and the oblique stacking (Fig. 2.1). By proper stacking for air circulation, culms can be dried with no need to add energy above the capacity of the ambient air. However, it has some disadvantages. Drying time is long, ranging from several weeks to several months for the required moisture content. During air-drying, splits can occur and culms can be infected by fungi, especially moulds. The air-drying depends largely on the climatic conditions. Since the weather cannot be regulated, there is little control over the drying process. The air-drying conditions are difficult for reaching a moisture content below about 12% as required for later processing (Gandhi, 1998; Montoya Arango, 2006).

Fig. 2.1. Stacking bamboo culms for air-drying under cover and open
(Bamboo Arts and Craft Network)

Kiln drying

Kiln seasoning is the drying of bamboo culms in a closed chamber with controlled temperature, relative humidity and air circulation. Combinations of desired air temperature and relative humidity are known as the kiln schedule. As the moisture content decreases, the schedule is progressively made more severe.

Kiln drying normally takes 6 - 15 days, depending on the bamboo species, the kiln and the schedule being used (Laxamana, 1985; Montoya Arango, 2006). Kiln drying enables to dry bamboo to any moisture content. For large-scale operations with high-level bamboo quality kiln drying is more efficient than air-drying.

With a growing demand of large quantities of high quality products for export, some big bamboo manufacturers in South Vietnam have expanded their kiln drying. Especially, the Bamboo Nature Company, where the bamboo drying experiments of this study were carried out, has recently installed a drying system with 15 kilns.

Consequently, experiments on kiln drying were undertaken to obtain practical results.

2.1.3 Research on preservation and drying in Vietnam

Bamboo preservation

The earliest research on bamboo preservation in Vietnam was carried out by Nguyen (1964), who developed the gravity method for preservative treatment of fresh bamboo culms.

The next study was conducted by Pham (1974) on culm treatment with creosote for electricity poles. Preservation of *Dendrocalamus barbatus* by soaking and the Boucherie method was reported by Le (1976). The protection of fresh culms of *Bambusa balcoa* and *Neohouzeaua* sp. stored for pulping was undertaken by Nguyen (1977).

The increase of bamboo utilization in the 2000s, led to further research on bamboo preservation. Nguyen (2002) reported the treatment technique of *D. barbatus* and *B. stenostachya* by the gravity method for fresh culms as well as soaking and pressure methods for bamboo splits. An investigation on preservation of *D. barbatus* by soaking was conducted by Le and Bui (2006).

Recently, the Faculty of Forest Products Processing, Vietnam Forestry University in cooperation with the Institute of Wood and Paper Technology, University of Technology Dresden, has undertaken research on the thermal modification of the bamboos *D. barbatus* and *D. asper*.

Bamboo drying

In Vietnam, only Pham (2006) investigated kiln drying for *Bambusa procera* and *B. stenostachya* and provided kiln drying schedules for culm parts and culm splits without preservative.

Little research has been done so far on bamboo drying worldwide. Rehman and Ishaq (1947) studied air seasoning of the species *Dendrocalamus strictus, Bambusa arundinacea, B. butans* and *B. tulda*. An investigation on air-drying and kiln drying culm parts of several species was done by Glenn et al. (1954), giving a classification of the drying rate into three categories: high, intermediate and low. Laxamana (1985) researched culm parts and splits of *Bambusa* *vulgaris, Dendrocalamus merillanus*, *Phyllostachys nigra* and *Schizostachyum diffusum* by air-drying and kiln drying and reported that the drying rate is influenced by species as well as by the drying condition. Sharma (1988) explored the seasoning of some Indian bamboo species. Later studies were done by Wu (1992) on high-temperature drying round bamboo of *Phyllostachys makinoi*, Yosias (2002) on drying of *Bambusa blumeana*, and Montoya Arango (2006) on drying round and split culms of *Guadua angustifolia* by air-drying, solar drying and kiln drying.

In summary, the review indicates that there is little research done in Vietnam on bamboo preservation and drying. The current practices of the bamboo industry need comprehensive studies for improving the treatment of the raw material used for construction and furniture production.

2.2 Statement of problems

The Five Million Hectares Reforestation National Program from 2006 - 2010 underlined bamboo as one of the most notable species for plantation. One of the purposes of this project is to increase the bamboo resources and to expand their usage by the bamboo industry in Vietnam (Do, 2006). Consequently, appropriate industrial processing technologies have to be developed. A key step for processing high-value products is the treatment of the material. However, the treatment of bamboo in Vietnam comprises only simple techniques which usually cannot ensure international quality standards. In addition, they are not adequate to industrial manufacturing due to low efficiency. Little research has been undertaken so far on preservation and drying of bamboo in Vietnam.

The tropical climate in Vietnam with high temperatures and relative humidity facilitates fungal growth on bamboo material. Pentachlorophenol was widely used for short-term protection. However, this chemical has been banned in Vietnam as well as in many parts of the world due to its high toxicity (Tang, 2009). Thus, bamboo manufacturers have difficulties in protecting bamboo from fungi which leads to many problems with bamboo storage and culm exportation. Hence, manufacturers urgently need cost-effective and also environment-friendly treatment methods.

For furniture making, culm parts are treated with a preservative using the pressure process, mostly with only one schedule for various bamboo species (Tang, 2009). Such a treatment does not consider the different properties of the species in the impregnation schedule. An improper treatment may not ensure the desired quality. For example, low pressure may not guarantee the required quantity of preservative up-take, whereas a high pressure can cause cracks and collapse (Singh and Tewari, 1979). Thus, it is necessary to determine an adequate treatment schedule for the species used.

Drying is essential to the treatment of bamboo material for any use. It helps to ease the further steps in the manufacturing process, such as machining and finishing. Air-drying is usually applied in rural areas and in bamboo factories with small capacities, but it has some disadvantages such as a long drying time, the large dependence on climatic conditions, and the difficulty in obtaining the target moisture content. Furthermore, air-drying is not adequate for large-scale production. It therefore cannot satisfy the continuously increasing demand of bamboo products. Kiln drying overcomes the limitations of air-drying. It has recently been expanded in industrial bamboo manufacturing. However, considerable problems exist in the drying techniques due to little research in this field.

To contribute to the development of the bamboo industry in Vietnam, an investigation was undertaken on short-term protection, on preservative treatment, and drying of the major commercial bamboo species.

2.3 Objectives

The objectives of the study are the development of suitable treatment methods for the most popular commercial bamboo species in Vietnam. The work aims to investigate different formulas for short-term bamboo protection, and explores various schedules for preservation and drying of bamboo culm parts. The ultimate goal is to obtain effective protection and appropriate drying schedules for the treatment of the major commercial bamboo species, thus ensuring treated bamboo with desired technical specifications for a large-scale production.

The objectives have been achieved by fulfilling the following works:

- investigating the short-term protection of bamboo materials against fungi with environment-friendly chemicals under laboratory and field tests,
- investigating proper schedules for the preservative treatment of bamboo culm parts by pressure process,
- investigating suitable kiln drying schedules for bamboo culm parts.

3. EXPERIMENTS AND RESULTS

The research concerns three separate fields of bamboo treatment: 1) the short-term protection of bamboo against fungi; 2) the preservative treatment of bamboo culm parts by pressure process; 3) the kiln drying of bamboo culm parts. The results were published in five peer-reviewed papers as attached at the end.

This chapter presents an overall summary of the methodologies and results obtained from the research. They are detailed in the related publications.

3.1 Short-term protection of bamboo against fungi (Publications 1 and 2)

The investigation was carried out as laboratory experiments with small samples in the Centre of Wood Science, University Hamburg, and as field tests with larger samples in the factory of Bamboo Nature Company in Binh Duong province, South Vietnam.

3.1.1 Laboratory experiments (Publication 1)

3.1.1.1 Methodology

From fresh culms of the two bamboo species *B. stenostachya* and *T. siamensis*, samples of 70 mm length were taken halfway between the internodes and split lengthwise. Acetic, boric, citric, formic, propionic, sorbic acid, and the salts potassium citrate, sodium acetate, sodium borate and sodium propionate were applied in 21 formulas.

Two specimens of each bamboo species were dipped for 5 min in the respective treatment solution. They were exposed in two test series. For one test series, artificial infection with a water-based mixture of conidia of six moulds *Aspergillus niger*, *A. flavus*, *A. oryzae, Aspergillus* sp., *Paecilomyces variotii*, and *Penicillium* sp. (Fig. 3.1) was done with a small brush. These six moulds were isolated from natural growth on bamboos and were provided by the Microorganism Laboratory of Nong Lam University of Ho Chi Minh City, Vietnam. The other series contained only the natural flora. The exposure was done in an incubation room at 30 °C and 75% RH (Fig. 3.2). The development of mould growth on the surface of the specimens was assessed after 1, 2, 4 and 8 weeks according to the rating scheme of the British Standard Institution 2005.

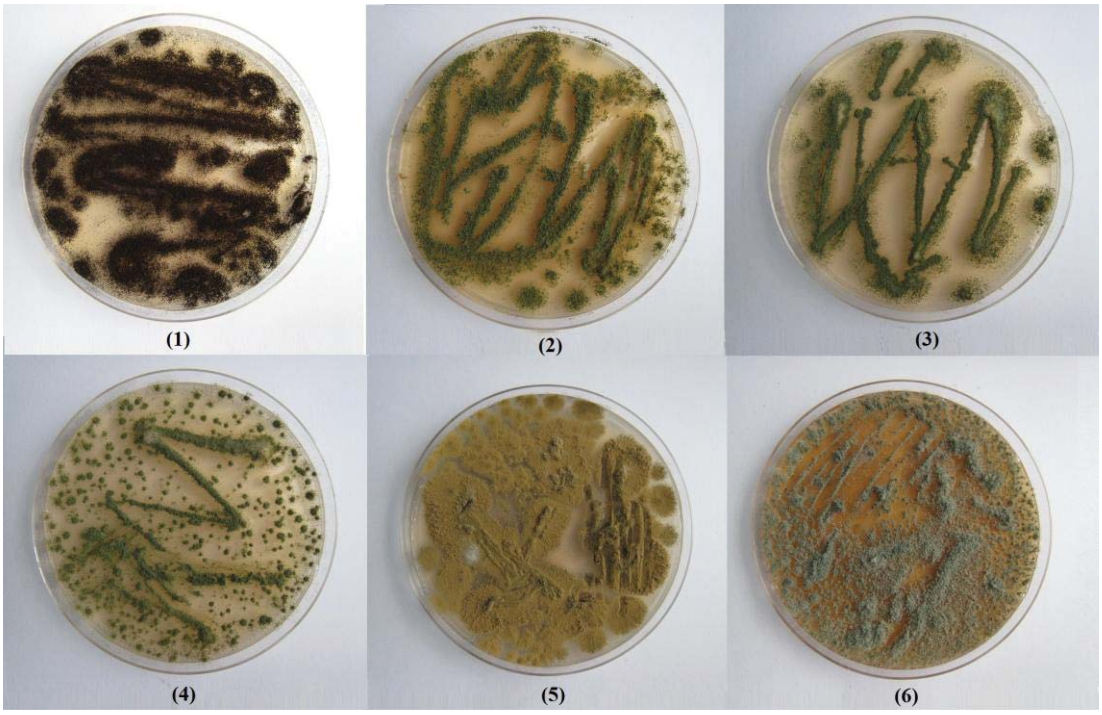

Fig. 3.1. Moulds for testing

(1) *Aspergillus niger*; (2) *A. flavus*; (3) *A. oryzae*; (4) *Aspergillus* sp.; (5) *Paecilomyces variotii*; (6) *Penicillium* sp.

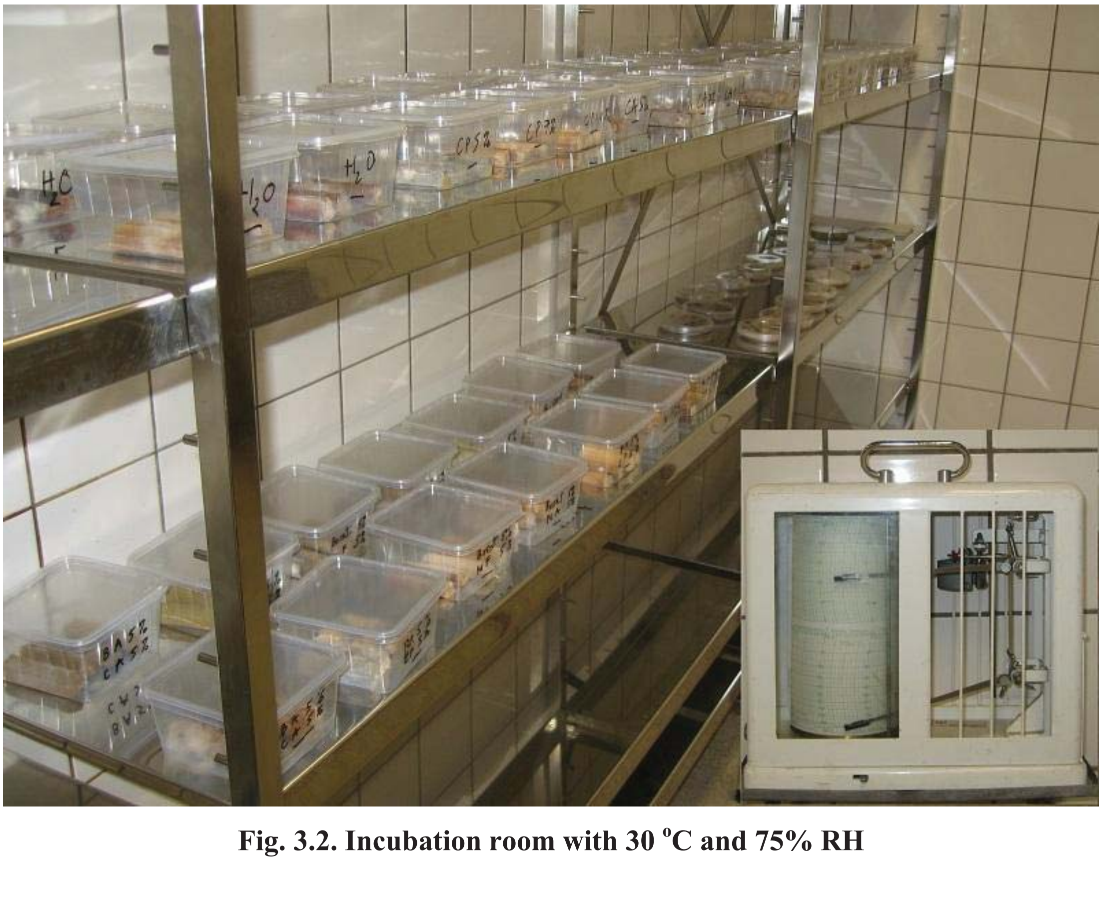

Fig. 3.2. Incubation room with 30 °C and 75% RH

3.1.1.2 Results

The results of both test series "artificial infection" and "natural mould flora" for *T. siamensis* and *B. stenostachya* are summarized in Table 3.1. The treatments with 10% acetic acid, 7% propionic acid as well as with a mixture of 3% boric acid and 7% propionic acid totally prevented mould growth over the whole incubation period of 8 weeks. All other treatments led to severe or very severe mould growth. The two bamboo species behaved rather similarly regarding mould susceptibility and prevention. As an exception, the mixture of 3% boric acid and 7% acetic acid showed moulded specimens of *T. siamensis* and clean specimens of *B. stenostachya*.

Table 3.1. Efficacy of anti-mould treatments for two species *T. siamensis* and *B. stenostachya*

Formulas	pH -value	Incubation after 8 weeks			
		Thyrsostachys siamensis		*Bambusa stenostachya*	
		artificial infection	natural mould flora	artificial infection	natural mould flora
7% acetic acid (AA)	3.0	4	3	4	3
10% AA	2.8	0	0	0	0
7% citric acid (CA)	2.7	4	4	4	4
10% CA	2.6	4	4	4	4
7% formic acid (FA)	3.8	4	4	4	4
10% FA	3.7	4	4	4	4
7% propionic acid (PA)	2.9	0	0	0	0
10% PA	2.8	0	0	0	0
0.6% sorbic acid (SA)	3.7	4	4	4	4
7% Na-acetate (NA)	8.4	4	4	4	4
10% NA	8.5	4	4	4	4
7% Na-propionate (NP)	8.0	4	4	4	4
10% NP	8.1	4	4	4	4
2% boric acid (BA) + 3% Na-borate	8.7	4	4	4	4
3% BA + 7% NP	7.0	4	4	4	4
3% BA + 7% NA	7.9	4	4	4	4
3% BA + 7% K-citrate	8.3	4	4	4	4
3% BA + 7% AA	3.0	3	2	0	0
3% BA + 0.3% SA	3.9	4	4	4	4
3% BA + 7% CA	2.5	4	4	4	4
3% BA + 7% PA	3.0	0	0	0	0
H_2O	-	4	4	4	4

The efficacy of various formulas is obviously not only due to a particular chemical, but also influenced by the pH-value. The effective formulas had pH-values between 2.8 and 3.0: 10% acetic acid with pH 2.8 and propionic acid with pH 2.8/2.9. Their salts, 10% sodium acetate (pH 8.5) and sodium propionate (pH 8.0/8.5), had no protective effect. Sun et al. (2011) also concluded that hydrochloric acid provides good protection for bamboo compared with sodium hydroxide.

For the laboratory experiments, the specimens were infected only once. Under field conditions with larger samples, bamboo would be exposed to permanent infection pressure from the surrounding air, so that the applied concentrations might not meet those conditions. Therefore, the effective formulas of 10% acetic acid, 7% and 10% propionic acid, the mixture of 3% boric acid and 7% acetic acid as well as the of 3% boric acid and 7% propionic acid were further investigated in field trials.

The results of the laboratory experiments were presented in Publication 1 “Environment-friendly short-term protection of bamboo against moulding”.

3.1.2 Experiments for field tests (Publication 2)

3.1.2.1 Methodology

Samples were prepared from fresh culms of four bamboo species, *B. stenostachya, B. procera, D. asper* and *T. siamensis,* as culm parts or splits of 60 and 120 cm length. The epidermis was removed by sanding.

The effective chemicals from the previous laboratory experiments (acetic, boric and propionic acids) were applied. The bamboo samples were dipped for 10 min in the treatment solutions (Fig. 3.3), then bundled and placed on supports over wet soil ground. After one day of exposure to natural infection, the samples were covered with a plastic sheet to avoid sunlight and drying. The test was carried out in a roof-covered raw material storage area in the factory of the Bamboo Nature Company.

The tests were done in three periods, each of 8 weeks during the rainy season in 2009 (June – August, July – September and September – November). The temperature during exposure was about 28 °C and the relative humidity was between 80 and 90%. The development of mould growth on the surface of the specimens was assessed after 1, 2, 4 and 8 weeks.

Fig. 3.3. Dipping samples into the test solutions and covering by plastic

3.1.2.2 Results

The result of the field tests is summarized in Table 3.2. Treatments with 10% acetic acid and 7% propionic acid completely inhibited mould growth on *B. stenostachya* and *T. siamensis.* For full protection of *B. procera* and *D. asper,* 10% propionic acid was necessary.

Table 3.2. Efficacy of antimould treatments for culm parts of four bamboo species in field test

Organic acid	Period*	Exposure time after 8 weeks			
		B. stenostachya	*B. procera*	*D. asper*	*T. siamensis*
Acetic acid 10%	I	0	2	2	0
	II	0	3	3	0
	III	0	2	2	0
Propionic acid 10%	I	0	0	0	0
	II	0	0	0	0
	III	0	0	0	0
Propionic acid 7%	I	0	2	2	0
	II	0	3	3	0
	III	0	2	2	0
Boric acid 3% + acetic acid 7%	I	0	4	4	1
	II	1	4	4	3
	III	2	3	3	3
Boric acid 3% + propionic acid 7%	I	0	1	1	0
	II	0	2	2	0
	III	0	1	1	0
Control	I	2	3	3	2
	II	3	4	4	3
	III	4	3	3	4

*Test period in 2009, each lasting eight weeks:
I = June-August, II = July-September, and III = September-November

In summary, a short-term protection of culm parts can be achieved by simple treatment with environment-friendly chemicals. The treated bamboos were prevented from moulding during the exposure period of at least eight weeks. The environmental-friendly acids, especially 10% propionic acid, were effective in inhibiting mould growth. The proposed method is economical because the costs of the acids are acceptable. Further investigations should deal with the possible consequences of the treatment for subsequent bamboo use in long-term service, including the influence on colour, smell and gluing ability of parquets.

The results of the field experiments were presented in the Publication 2 "Protection of bamboo against mould using environment-friendly chemicals".

3.2 Preservative treatment of bamboo culm parts by pressure process (Publication 3)

The sample preparation and the various treatment schedules were carried out at the factory of the Bamboo Nature Company, Binh Duong province and at the Faculty of Forestry, Nong Lam University in Ho Chi Minh City, Vietnam. A detailed working plan and the treatment parameters were outlined locally before the treated samples were sent to the Centre of Wood Science, University Hamburg, Germany, for further analytical investigations.

3.2.1 Methodology

Samples of culm parts of 120 cm length were taken from the bottom and middle portion of 3-year-old culms of *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*. For the species *B. stenostachya* and *D. asper*, the diaphragms were fractured. The material was first air-dried for about 5 weeks. Then, the skin was removed by machine sanding. The influence of the moisture content was investigated for two ranges, 30 - 40% and 15 - 20%. Two solutions were tested, for indoor furniture 6% BB as mixture of borax and boric acid, and for outdoor structures 6% CCB containing sodium dichromate, copper sulphate and boric acid.

The experiments were conducted in a vacuum pressure cylinder of 40 cm in diameter and 140 cm in length (Fig. 3.4). For fifteen impregnation schedules the absorption of the preservatives was evaluated.

Fig. 3.4. Impregnation of the middle parts of *Dendrocalamus asper* and the bottom parts of *Thyrsostachys siamensis* in a treatment cylinder

3.2.2 Results

The preservative uptake of the culm parts was influenced by the species, culm portion, moisture content, preservative, and especially depended on pressure and time. Statistical analysis revealed that the retention is linearly proportional to the applied pressure and time. The absorption of the three species by pressure from 2.5 to 8.5 bar is listed in Table 3.3.

Table 3.3. Average retention (kg/m³) of three bamboo species treated with BB and CCB by pressures from 2.5 to 8.5 bar for 60, 90 and 120 min

Bamboo species	Culm parts		Pressure (bar) / Time (min)	BB					CCB				
				2.5	**4**	**5.5**	**7**	**8.5**	**2.5**	**4**	**5.5**	**7**	**8.5**
B. stenostachya	B	MC2	**60**	3.1	3.9	5.1	6.8	9.4	3.5	5.1	6.8	10.1	12.2
			90	3.4	4.4	5.9	7.7	10.9	3.7	5.9	7.5	10.9	13.4
			120	3.6	4.8	6.7	8.9	11.4	4.1	6.5	8.5	12.0	13.8
		MC1	**60**	3.4	4.4	5.7	7.5	10.1	4.1	5.4	7.3	10.9	13.0
			90	3.7	4.8	6.3	8.4	11.9	4.3	6.1	8.5	11.9	14.2
			120	4.2	5.4	7.1	9.5	12.7	4.7	6.7	9.0	12.7	14.6
	M	MC2	**60**	3.6	4.6	5.8	7.8	10.3	3.7	6.2	7.2	10.8	13.7
			90	3.9	4.8	6.2	8.9	11.7	4.9	6.5	8.6	12.0	14.4
			120	4.3	5.4	7.4	9.7	12.5	5.1	7.0	9.8	13.1	14.9
		MC1	**60**	4.0	5.3	6.5	9.2	11.7	4.1	6.7	8.7	11.8	14.7
			90	4.6	5.7	7.0	10.2	12.8	5.2	7.1	9.6	13.0	15.5
			120	4.7	6.2	8.4	11.3	13.8	5.5	7.9	10.7	14.1	15.9
D. asper	B	MC2	**60**	2.7	3.6	4.7	6.2	8.1	3.4	4.4	6.0	8.5	11.3
			90	3.1	4.0	5.5	6.6	9.2	3.5	4.9	6.6	9.5	11.7
			120	3.3	4.3	5.8	7.9	10.0	3.7	5.7	7.7	10.9	13.1
		MC1	**60**	3.1	3.9	5.0	7.0	9.4	3.9	4.8	6.9	9.9	12.2
			90	3.4	4.4	5.8	7.8	10.2	4.1	5.4	7.8	11.0	12.4
			120	3.7	4.7	6.7	8.8	11.2	4.0	6.2	8.0	11.5	14.0
	M	MC2	**60**	3.0	4.0	5.3	6.7	9.2	3.7	5.1	6.6	9.0	11.9
			90	3.3	4.3	6.0	7.5	9.7	4.2	5.6	7.5	10.2	12.9
			120	3.8	4.5	6.4	8.4	10.8	4.3	6.2	8.4	11.3	13.9
		MC1	**60**	3.4	4.4	5.8	7.7	10.7	4.2	5.5	7.3	10.7	13.2
			90	3.7	4.6	6.2	8.5	11.2	4.4	6.1	8.7	11.6	14.2
			120	4.0	5.3	7.0	9.8	11.9	4.9	6.8	9.1	12.8	14.4
T. siamensis	B	MC2	**60**	3.6	4.4	5.6	7.8	11.7	3.9	5.5	7.9	10.9	13.5
			90	3.7	4.7	6.2	9.2	12.1	4.3	6.2	9.1	11.5	14.3
			120	3.2	5.2	7.2	10.2	12.7	5.1	7.0	10.3	12.9	14.9
		MC1	**60**	3.7	4.7	6.2	9.1	12.0	4.4	6.2	8.6	11.5	14.1
			90	4.2	5.2	7.1	10.4	12.5	4.5	6.6	10.1	12.9	14.9
			120	3.7	5.6	7.8	11.1	13.2	5.9	7.5	11.1	13.7	15.5
	M	MC2	**60**	3.9	5.5	7.1	9.3	13.0	5.1	7.1	8.8	11.8	15.4
			90	4.6	6.0	7.5	10.7	13.8	5.9	7.5	9.9	12.8	16.1
			120	4.5	6.6	9.1	11.6	14.4	6.1	7.9	11.2	14.4	16.4
		MC1	**60**	4.5	6.0	7.9	11.0	13.5	5.5	7.9	10.5	13.1	16.3
			90	5.1	6.9	8.9	12.1	14.3	6.1	8.5	11.9	14.5	17.1
			120	5.4	7.4	9.6	12.8	15.5	6.5	9.1	12.9	15.9	17.5

B: Bottom; M: Middle; MC1: 15 – 20%; MC2: 30 – 40%

For practical applications, a moisture range of 30 - 40% could be used instead of 15 - 20% as sometimes applied, thus reducing seasoning time. The preservation of bamboo treated with 4 kg/m^3 BB for indoor furniture and 10 kg/m^3 CCB for outdoor exposure, as recommended by Liese and Kumar (2003), requires the following treatment schedules:

For indoor use with BB, *T. siamensis* needs a pressure of 4 bar for 60 minutes, whereas for *B. stenostachya* and *D. asper* 5.5 bar for 60 minutes is required.

For outdoor application with CCB, *T. siamensis* demands a pressure of 5.5 bar for 120 minutes, but *B. stenostachya* and *D. asper* need 7 bar for 60 and 120 minutes, respectively.

Furthermore, the relationship between pressure, time and retention was determined using regression analysis resulting in a high coefficient (R^2 > 95%) as shown in Table 3.4.This information could be applied for determining the treatment schedule for the species investigated relevant to the required retention.

Table 3.4. Regression equations for the retention of three bamboo species with two preservatives (at 95% confidence level)

Species	Position	MC (%)	Preservatives			
			BB		CCB	
			Linear regression equation	R^2	Linear regression equation	R^2
B. stenostachya	Bottom	30 - 40	$y= - 2.25 + 1.18\ x_1 + 0.02\ x_2$	0.957	$y= - 2.66 + 1.59\ x_1 + 0.02\ x_2$	0.975
		15 - 20	$y= - 2.32 + 1.28\ x_1 + 0.02\ x_2$	0.953	$y= - 2.34 + 1.66\ x_1 + 0.02\ x_2$	0.982
	Middle	30 - 40	$y= - 2.01 + 1.26\ x_1 + 0.02\ x_2$	0.959	$y= - 2.44 + 1.66\ x_1 + 0.03\ x_2$	0.983
		15 - 20	$y= - 1.98 + 1.41\ x_1 + 0.03\ x_2$	0.967	$y= - 2.15 + 1.77\ x_1 + 0.03\ x_2$	0.993
D. asper	Bottom	30 - 40	$y= - 1.65 + 1.01\ x_1 + 0.02\ x_2$	0.966	$y= - 2.79 + 1.44\ x_1 + 0.02\ x_2$	0.975
		15 - 20	$y= - 1.97 + 1.15\ x_1 + 0.02\ x_2$	0.965	$y= - 2.12 + 1.54\ x_1 + 0.02\ x_2$	0.977
	Middle	30 - 40	$y= - 1.52 + 1.09\ x_1 + 0.02\ x_2$	0.97	$y= - 2.43 + 1.48\ x_1 + 0.02\ x_2$	0.98
		15 - 20	$y= - 1.86 + 1.27\ x_1 + 0.02\ x_2$	0.967	$y= - 2.16 + 1.63\ x_1 + 0.02\ x_2$	0.983
T. siamensis	Bottom	30 - 40	$y= - 1.66 + 1.00\ x_1 + 0.02\ x_2$	0.966	$y= - 2.61 + 1.67\ x_1 + 0.03\ x_2$	0.993
		15 - 20	$y= - 2.17 + 1.49\ x_1 + 0.02\ x_2$	0.97	$y= - 2.27 + 1.71\ x_1 + 0.03\ x_2$	0.989
	Middle	30 - 40	$y= - 2.25 + 1.55\ x_1 + 0.02\ x_2$	0.974	$y= - 1.46 + 1.73\ x_1 + 0.02\ x_2$	0.983
		15 - 20	$y= - 1.77 + 1.60\ x_1 + 0.02\ x_2$	0.987	$y= - 1.24 + 1.86\ x_1 + 0.03\ x_2$	0.992

y is retention (kg/m^3); x_1 is pressure intensity (bar) and x_2 is pressure time (minute) with $2.5 < x_1 < 8.5$ and $60 < x_2 < 120$

The results were presented in Publication 3 “Pressure treatment of bamboo culms of three Vietnamese species with boron and CCB preservatives”.

3.3 Kiln drying of bamboo culm parts (Publications 4 and 5)

Kiln drying was investigated with culm parts without skin of the species *B. stenostachya, D. asper* and *T. siamensis*. A detailed working plan and the drying schedules were outlined at the Centre of Wood Science, University Hamburg. The investigation was done with pilot-kiln-drying for short and untreated culm parts and with industrial kiln-drying for longer culm parts treated with boron at the factory of the Bamboo Nature Company. Further analytical investigations were conducted at the Centre for Research and Transfer of Technology for Forest Products Processing, Nong Lam University.

3.3.1 Pilot-kiln drying (Publication 4)

3.3.1.1 Methodology

Samples of 140 cm length were cut from the bottom and middle parts of culms. The experiments were performed in a pilot dry–kiln (Fig. 3.5). The drying schedules applied had four intensities: “mild”, “relatively mild”, “severe” and “highly severe” (Table 3.5). For each of three bamboo species, different schedules were tested. Schedule no.1 with mild drying was applied to the cavity species *B. stenostachya* and *D. asper*. Schedule no. 2 with relatively mild drying and schedule no. 3 with severe drying were applied to these cavity species and also to the solid species *T. siamensis*. Schedule no. 4 with highly severe drying conditions was tested only on *T. siamensis*.

Table 3.5. The conditions (set–point values) of four drying schedules

Step	Moisture content (%)	No.1 mild		No.2 relatively mild		No.3 severe		No.4 highly severe	
		T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	Over 90	45	80	50	80	55	80	65	80
2	90 – 70	45	70	50	70	55	75	65	60
3	70 – 50	50	60	60	60	60	65	70	45
4	50 – 40	50	50	60	50	65	50	70	35
5	40 – 30	50	40	60	30	65	35	70	30
6	30 – 20	55	40	65	30	70	25	75	25
7	20 –10	55	30	65	20	70	20	75	15
Conditioning with 50 ^{o}C T and 70% RH									

Fig. 3.5. Pilot dry–kiln for the experiments

3.3.1.2 Results

The results for the pilot kiln drying of the three bamboo species are summarized in Table 3.6.

Table 3.6. Summary of the results for the pilot kiln drying with three bamboo species

Schedule	Result	*Bambusa stenostachya*		*Dendrocalamus asper*		*Thyrsostachys siamensis*	
		Bottom	Middle	Bottom	Middle	Bottom	Middle
No. 1 mild	IMC (in %)	103	92	102	89	-	-
	FMC (in %)	10.4	10.1	9.3	8.2	-	-
	Defect (in %)	3.7	1.9	4.9	3.5	-	-
	Time (in hours)	350	326	370	302	-	-
No. 2 relatively mild	IMC	102	99	105	93	120	110
	FMC	9.6	9.5	9.2	10.4	8.5	10.1
	Defect	5.1	2.9	17.8	12.5	2.5	1.6
	Time	272	255	303	259	292	222
No. 3 severe	IMC	105	96	108	92	119	106
	FMC	9.6	8.3	10.2	9.2	9.7	10.3
	Defect	15.7	18.9	28.9	19.5	4.8	3.9
	Time	255	208	282	236	245	195
No. 4 highly severe	IMC	-	-	-	-	120	108
	FMC	-	-	-	-	8.8	10.2
	Defect	-	-	-	-	5.5	4.2
	Time	-	-	-	-	219	176

IMC: Initial moisture content; FMC: Final moisture content

For *T. siamensis* with an initial moisture content (MC) of over 100% the drying time for a final MC of 10% with a highly severe drying schedule no. 4 was 7 days for the middle part and 9 days for the bottom part. *D. asper* is most difficult to dry and severely susceptible to checks and splits, so that it needed the mild drying schedule no. 1 with 13 days for the middle and 16 days for bottom part. *B. stenostachya* dried moderately using the relatively mild drying schedule no. 2 with 10 days for the middle and 12 days for the bottom part.

The results of the pilot-kiln drying were presented in Publication 4 "Investigation on optimisation of kiln drying for the bamboo species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*".

3.3.2 Industrial kiln drying (Publication 5)

The effective and feasible schedules of each species from the pilot kiln experiments were further investigated for drying longer culm parts treated with preservatives in industrial dry kilns.

Fig. 3.6. Stacked culm parts of *Thyrsostachys siamensis* for industrial kiln drying

3.3.2.1 Methodology

Culm parts without skin of 2.0 and 2.2 m length, treated with boron (BB), were taken as these are mainly used for products by the Bamboo Nature Company. The experiments were done in industrial dry kilns (Fig. 3.6). Each kiln load contained six wagons with one species. For each species, two schedules were tested; the “relatively mild” schedule no. 2 for *B. stenostachya* and *D. asper*, the “severe” schedule no. 3 for all three species, and the “highly severe” schedule no. 4 only for *T. siamensis*. Similarly, the moisture loss, drying time and drying defects were determined. For industrial kiln drying, the final moisture content was determined according to EN 14298 for the timber-drying quality requirement.

3.3.2.2 Results

The results for the industrial kiln drying of three bamboo species are summarized in Table 3.7.

Table 3.7. Summary of the industrial kiln drying of three bamboo species

Schedule	Result	*B. stenostachya*	*D. asper*	*T. siamensis*
No. 2 relatively mild	IMC (in %)	125	120	-
	FMC (in %)	9	10	-
	Defect (in %)	5	8	-
	Time (in hours)	303	327	-
No. 3 severe	IMC	119	118	120
	FMC	11	9	9
	Defect	7	21	5
	Time	254	279	236
No. 4 highly severe	IMC	-	-	127
	FMC	-	-	7
	Defect	-	-	6.5
	Time	-	-	198

IMC: Initial moisture content; FMC: Final moisture content

The drying rate revealed notable differences between the three species, as has also been demonstrated in the pilot experiments with shorter culm parts. The bamboo *T. siamensis* dried fastest, followed by *B. stenostachya* and *D. asper*. This can be explained by the differences in specific gravity and structural features. The studies on bamboo seasoning by Glenn et al. (1954) and Laxamana (1985) showed a faster drying rate for bamboo species with a lower specific gravity and shorter internodes.

With the relatively mild schedule no. 2, the drying time of *B. stenostachya* added up to 303 hours for reducing the initial MC from 125 to 9%, with 5% drying defects percentage of the culm parts. Bamboo *D. asper* dried in 327 hours with a reduction of MC from 120 to 10%, and 8% drying defects percentage. Schedule no. 2 was not applied for *T. siamensis* as the previous experiments had shown that this species can be dried using a more severe drying intensity.

By applying the severe schedule no. 3, the drying time for *B. stenostachya* was reduced to 254 hours with 7% drying defects, for *D. asper* to 279 hours with 21%, and for *T. siamensis* 236 hours with 5% drying defects.

The highly severe schedule no. 4 was only used for *T. siamensis* resulting in a drying time of 198 h with 6.5% drying defects. This schedule was not applied for *B. stenostachya* and for *D. asper* due to severe defects experienced for shorter culm parts.

Ideally, the moisture distribution within a kiln-dried culm part should be uniform. However, in practice moisture gradients occur due to the faster moisture evaporation from the ends and culm surface compared to the diffusion rate from the middle section towards the ends and from the inner culm towards its surface. Results showed that the moisture at the middle section was slightly higher than at the ends. The average moisture gradient for the different kiln runs ranged from 1.0 to 1.3% with a standard deviation 0.2 to 0.4.

Successful kiln drying requires an appropriate drying schedule and also the control of temperature and relative air humidity. As shown for the three bamboos in the Fig. 3.7 to Fig. 3.9 the drying conditions of the experiments were regulated relatively close to the setting values.

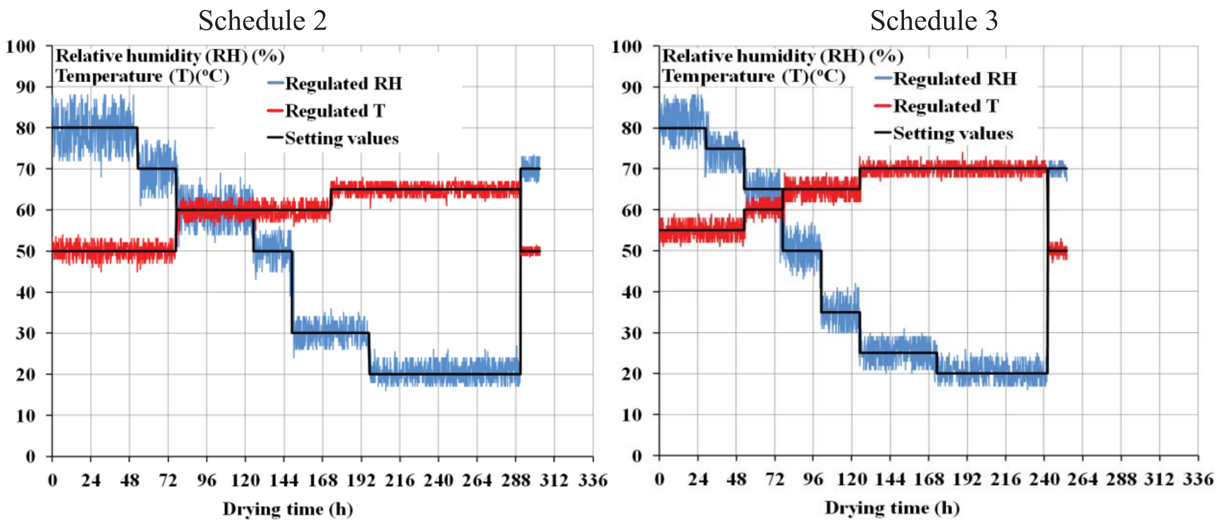

Fig. 3.7. Drying trends in experiments with *Bambusa stenostachya*

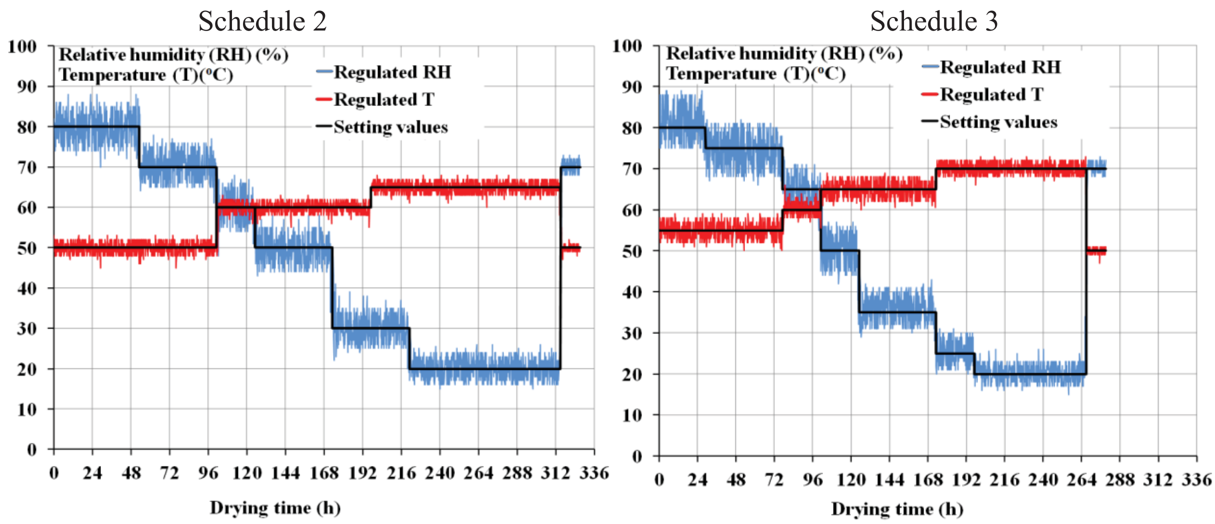

Fig. 3.8. Drying trends in experiments with *Dendrocalamus asper*

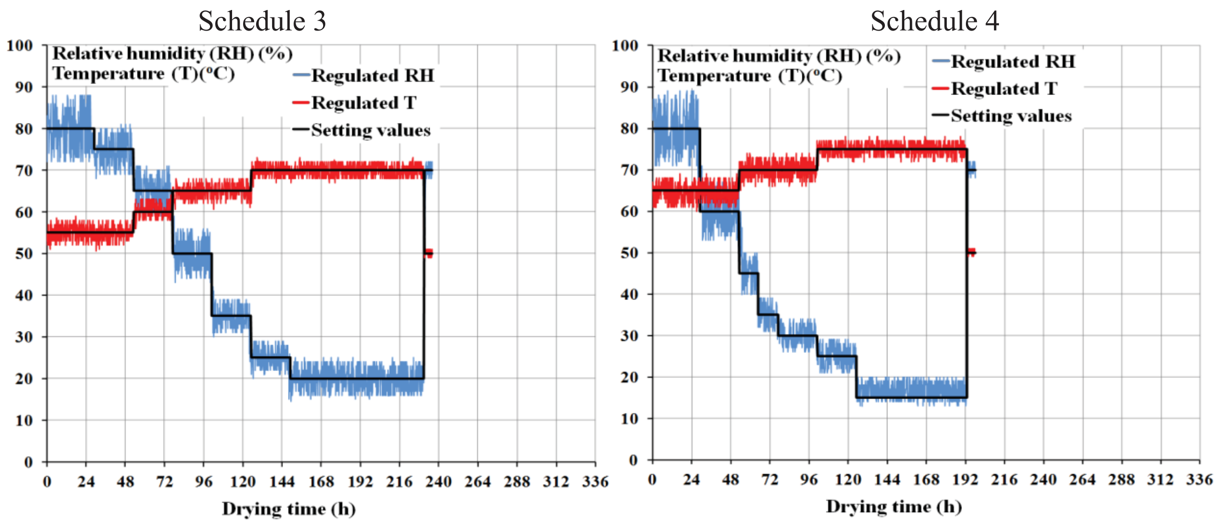

Fig. 3.9. Drying trends in experiments with *Thyrsostachys siamensis*

In summary, kiln drying of bamboo culm parts treated with boron (BB) can be applied successfully using suitable schedules of temperature and relative air humidity. All drying schedules investigated for the three species meet the specification for the final moisture content in EN 14298 (2004). Considering practical points for reducing seasoning time and defects, the following drying schedules are recommended:

B. stenostachya dries moderately fast using a severe schedule with an initial temperature of 55 °C and RH of 80% and a final temperature of 70 °C and 20% RH for 10 days.

D. asper is difficult to dry and susceptible to drying defects. It therefore needs a relatively mild schedule with an initial temperature of 50 °C and RH of 80% and a final temperature of 65 °C and RH of 20% for 13 days.

T. siamensis is easy to dry applying a highly severe drying schedule with an initial temperature of 65 °C and RH of 80% and towards the end with 75 °C and 15% RH for 8 days.

The results of the investigation on drying round bamboo in an industrial kiln were presented in Publication 5 “Kiln drying for bamboo culm parts of the species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*”.

Following this study, South Vietnamese bamboo processing companies with kiln drying facilities, such as Bamboo Nature Company and Bamboo Villages Co., have already applied these effective schedules for drying boron-treated culm parts.

The drying schedules should be further investigated for bamboo treated with CCB as well as other commercial species, such as *B. vulgaris* and *D. barbatus.*

4. CONCLUSIONS

This study addressed the treatment of the major commercial bamboo species in Vietnam. Effective methods for short-term protection, preservation and drying of bamboos were successfully developed. These methods ensure the required quality of treated bamboos and are suitable for a large-scale industrial production.

The short-term protection of bamboo can be done by treatment with low cost and environment-friendly chemicals: acetic acid and propionic acid. For *B. stenostachya* and *T. siamensis*, the treatment with 10% acetic acid or 7% propionic acid prevents mould growth for an exposure period of at least eight weeks, but for *B. procera* and *D. asper* 10% propionic acid is needed.

The preservative treatment of culm parts of the three bamboos, *B. stenostachya, D. asper* and *T. siamensis* was investigated for indoor and outdoor applications. The preservative absorption of the bamboos depends on the species, the culm portion, their moisture content, the preservative and especially the pressure and time applied. Statistical analysis revealed that the retention is linearly proportional to pressure and time. For bamboo treated with 4 kg/m^3 BB to be used indoor, *T. siamensis* needs a pressure of 4 bar for 60 minutes, whereas for *B. stenostachya* and *D. asper* 5.5 bar for 60 minutes is required. For outdoor application with 10 kg/m^3 CCB, *T. siamensis* demands a pressure of 5.5 bar for 120 minutes, but *B. stenostachya* and *D. asper* need 7 bar for 60 and 120 minutes.

Various kiln drying schedules for different culm portions of *B. stenostachya, D. asper* and *T. siamensis* were thoroughly tested in a pilot-kiln as well as in an industrial kiln. The most effective drying schedule was determined for each bamboo species, ensuring the required final moisture content and a low percentage of defects. *B. stenostachya* dries moderately fast using a severe schedule with an initial temperature of 55 °C and RH of 80% and a final temperature of 70 °C and RH of 20% for 10 days. *D. asper* is difficult to dry and needs a mild schedule with an initial temperature of 50 °C and RH of 80% and a final temperature of 65 °C and RH of 20% for 13 days. *T. siamensis* is easy to dry by applying a highly severe drying schedule with an initial temperature of 65 °C and RH of 80% and with a final temperature of 75 °C and 15% RH for 8 days.

The results of these studies were published in five peer-reviewed journals (see publication list).

Noteworthy: the pressure treatment of bamboo culm parts with BB and schedules for kiln drying of boron-treated culm parts have already been applied by two bamboo manufacturers in South Vietnam, the Bamboo Nature Company and Bamboo Villages Co.

Even though *B. stenostachya, B. procera*, *D. asper* and *T. siamensis* are the most popular commercial bamboo species in Vietnam, several other species, such as *B. vulgaris* and *D. barbatus,* are also used for furniture production and housing. The treatment of these species should be further investigated.

5. REFERENCES

Abd. Latif, M. and Liese, W. 1995. Utilization of bamboo. In: Abd. Razak, O., Abd. Latif, M., Liese, W. and Norini, H. (Eds.), Planting and Utilization of Bamboo in Peninsula Malaysia. FRIM Research Pamphlet. Forest Research Institute Malaysia, Kuala Lumpur, Malaysia (118):50-102.

Abd. Latif, M. and Zin, M.J. 1992. Culm characteristics of *Bambusa blumeana* and *Gigantochloa scortechinii* and its effects on physical and mechanical properties. In: Zhu, S., Li, W., Zhang, X. and Wang, Z. (Eds.), Bamboo and Its Use. Proceedings of International Symposium on Industrial Use of Bamboo, 7-11 December 1992, Beijing, China. International Tropical Timber Organization and Chinese Academy of Forestry, Beijing, China: 118-128.

Abd. Razak, O., Abd. Latif, M., Liese, W. and Naron, N. 1995. Planting and utilization of bamboo in peninsular Malaysia. Forest Research Institute Malaysia (FRIM), Kuala Lumpur, Malaysia (118): 118 pp.

Anwar, U.M.K., Zaidon, A., Hamdan, H. and Tamizi, M.M. 2005. Physical and mechanical properties of *Gigantochloa scortechinii* bamboo splits and strips. Journal of Tropical Forest Science 17(1): 12 pp.

British Standard Institution 2005. Wood preservatives determination of the preventive effectiveness against sapstain and mould fungi on freshly sawn timber field test. DD CEN/TS 15082: 18 pp.

Bui, T.T.K. 2006. Dac diem cau tao, thanh phan hoa hoc va tinh chat vat ly, co hoc cua tre Manh tong. Luan van Tot nghiep, Truong Dai Hoc Nong Lam TP. HCM: 60 pp.

De Vos, V. 2010. Bamboo material properties and market perspectives. Thesis Report of Larenstein University: 19-48.

Denrungruang, P. 2004. Chemical composition of five bamboo species in Thailand. Final Technical Report Project PD56/99 Rev.1 (I). Promotion of the Utilization of Bamboo from Sustainable Sources in Thailand. Royal Forest Department International Tropical Timber Organization, Bangkok, Thailand: 31-38.

Dinh, H.H., Hoang, V.A., Nguyen, P.H. and Le, T.H. 2011. Vietnam bamboo recourse assessment using remote sensing and policy implication for future development. Final Report. Vietnamese Institute of Policy and Strategy for Agriculture and Rural Development: 37 pp.

Do, V.B. 2006. Mot so loai tre thong dung cua Vietnam can chon de phat trien. Ban Tin Du An Trong Moi 5 Trieu Hectare Rung: 4-12.

Do, V.B. 2010. Tai nguyen tre Viet Nam. Vien Khoa Hoc Lam Nghiep: 114-152.

EN 14298 2004. Sawn timber-assessment of drying quality. European Committee for Standardization: 8 pp.

Environmental Bamboo Foundation (EBF) 2003. Vertical Soak and Diffusion (VSD) for Bamboo Preservation. Vs 3: 28 pp.

Espiloy, Z.B. 1985. Physico-mechanical properties and anatomical relationships of Philippine bamboo. In Rao, A.N., Dhanarajan, G. and Sastry, C.B. (Eds.), Recent Research on Bamboos. Proceedings of the 3rd International Bamboo Workshop, 6-14 October 1985, Hangzhou, China: 6-14.

Espiloy, Z.B. 1992. Properties affecting bamboo utilization. In: Zhu, S., Li, W., Zhang, X. and Wang, Z. (Eds.), Bamboo and Its Uses. Proceedings of the International Symposium on Industrial Use of Bamboo, 7-11 December 1992, Beijing, China. International Tropical Timber Organization. Chinese Academy of Forestry, Beijing, China: 139-142.

Gandhi, Y. 1998. Preliminary study on the drying of bamboo (*Bambusa blumeana*) in a wood waste-fired kiln. In: Proceedings of the 5th International Bamboo Congress and the 6th International Bamboo Workshop, 2-6 November 1998, San José, Costa Rica. INBAR (7):495-510.

Glenn, H.E., Brock, D.C., Byars, E.F. et al. 1954. Seasoning, preservative treatment and physical property studies of bamboo. Bulletin of Clemson College, Clemson, South Carolina (7):27-36.

Grosser, D. and Liese, W. 1971. On the anatomy of Asian bamboos, with special reference to their vascular bundles. Wood Science and Technology 5:290-312.

Ha, C.C. 2004. Bamboo - profuse material source for paper industry. Vietnam Non-Timber Forest Products Network (NTFP), NTFP-Newsletter 1: 1-6.

Hamdan, H., Hill, C.A.S., Zaidon, A., Anwar, U.M.K. and Abd. Latif, M. 2007. Equilibrium moisture content and volumetric changes of *Gigantochloa scortechinii*. Journal of Tropical Forest Science 19(1):18-24.

Ho, T.D. 2011. Nghien cuu xay dung che do say tre Tam vong (*Thyrsostachys siamensis*). Luan van Thac si, Truong Dai Hoc Nong Lam TP. HCM: 98 pp.

Hoang, T.T.H. and Tang, T.K.H. 2007. Structural features and physical properties of some important South Vietnam bamboo species. Journal Agriculture for Science Technology, Nong Lam University of HCM 3:15-22.

Hoogendoorn, C. 2012. Bamboo value chains. In: Proceedings of the 9th International Bamboo Congress, 10-13 April 2012, Antwerp, Belgium: 102-115.

Janssen, J.J.A. 1985. The mechanical properties of bamboo. In: Rao, A.N., Dhanarajan, G. and Sastry, C.B. (Eds.), Recent Research on Bamboos. Proceedings of the 3rd International Bamboo Workshop, 6-14 October 1985, Hangzhou, China: 250-256.

Kim, J.J., Lee, S.S., Ra, J.B., Lee, H., Huh, N. and Kim, G.H. 2011. Fungi associated with bamboo and their decay capabilities. Holzforschung 65:271-275.

Kishen, J., Ghosh, D.P. and Rehman, M.A. 1958. Studies in moisture content, shrinkage, swelling and intersection point of mature *Dendrocalamus strictus* (male bamboo). Indian Forest Records, Dehra Dun, India 1(2):11-30.

Kleist, G., Morris, I. and Murphy, R. 2002. Invasion and colonization of bamboo culm material by stain and decay fungi. International Research Group on Wood Preservation. IRG/WP/02-10453: 10 pp.

Kumar, S., Shukla, K.S., Dev, I. and Dobriyal, P.B. 1994. Bamboo preservation techniques: a review. Technical Report No. 3. International Network for Bamboo and Rattan (INBAR), New Delhi, India, and Indian Council of Forestry Research and Education (ICFRE), Dehra Dun, India: 59 pp.

Lahiry, A.K. 2005. Introducing bamboos for their importance and conservation. Document of the 36th Conference of International Research Group on Wood Protection, 24-28 April 2005, Bangalore, India: 28 pp.

Laxamana, M.G. 1985. Drying of some commercial Philippine bamboos. Journal Forest Products Research and Development Institute (FPRDI), Philippines 14 (1&2):8-19.

Le, V.U. 2010. Chuong trinh du an trong rung. Bo Nong Nghiep Phat Trien Nong Thon: 12-24.

Le, V.L. and Bui, V.A. 2006. Study on outdoor preservation of some bamboos and timbers used for making bearing piles, construction, raw material for furniture and artificial boards. Information on Forest Science and Technology No. 1: 111-126.

Le, V.N. 1976. Bao cao ket qua nghien cuu bao quan Luong trong xay dung. Ket Qua Nghien Cuu Cong Nghiep Rung (6): 1-10.

Liese, W. 1985. Bamboos - biology, silvics, properties, utilization. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany: 132 pp.

Liese, W. 1987. Research on bamboo. Wood Science and Technology 21:189-209.

Liese, W. 1988. Bamboo preservation in Costa Rica. Report of Project COS/87/001: 29 pp.

Liese, W. 1998. The anatomy of bamboo culms. Technical Report No. 18. The International Network for Bamboo and Rattan (INBAR), People's Republic of China: 204 pp.

Liese, W. and Grover, P.N. 1961. Untersuchungen über den Wassergehalt von indischen Bambushalmen. Ber. Deutsche Bot. Ges. 74:105-117.

Liese, W. and Grosser, D. 2000. An expanded typology for the vascular bundles of bamboo culms. In: Bamboo 2000. Proceedings of the International Symposium by Royal Project Foundation, 2-4 August 2000, Chiang Mai, Thailand: 121-134.

Liese, W. and Kumar, S. 2003. Bamboo preservation compendium. International Network for Bamboo and Rattan (INBAR), People's Republic of China: 230 pp.

Liese, W., Gutierrez, J. and Gonzales, G. 2002. Preservation of bamboo for the construction of houses for low-income people. In: Bamboo for Sustainable Development. Proceedings of the 5th International Bamboo Congress and the 6th International Bamboo Workshop, 2-6 November 1998, San José, Costa Rica. VSP and INBAR: 481-494.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H. and Wu, J. 2005. World bamboo resources – a thematic study prepared in the framework of the global forest resources assessment 2005. Non-Wood Forest Products (NWFPs). Food and Agriculture Organization of the United Nations (FAO), Rome, Italy (18): 73 pp.

Ma, X., Jiang, M. and Qin, D. 2010. The invasion channels of damage fungi in bamboo lumber. International Research Group on Wood Preservation, Stockholm. IRG/WP/10712: 7 pp.

Magel, E., Kruse, S., Lütje, G. and Liese, W. 2006. Soluble carbohydrates and acid invertases involved in the rapid growth of developing culms in *Sasa palmata* (Bean) Camus. Bamboo Science Culture 19:23-29.

Mohanan, C. 1997. Diseases of bamboos in Asia - an illustrated manual. Technical Report No. 10. International Network for Bamboo and Rattan (INBAR): 228 pp.

Montoya Arango, J.A. 2006. Trocknungsverfahren für die Bambusart *Guadua angustifolia* unter tropischen Bedingungen. PhD Dissertation University Hamburg: 243 pp.

Nguyen, H.N. 2006. Bamboos of Vietnam. Agricultural Publishing House, Hanoi: 2-5.

Nguyen, T.B.N. 2002. Investigation on preservation of bamboo used for construction. PhD Dissertation, Forest Science Institute of Vietnam, Vietnam: 44-51.

Nguyen, T.N. 2005. Khao sat tinh chat co hoc va vat ly cua tre Mo (*Bambusa vulgaris*), tre Gai (*Bambusa spinosa*), tre Tau (*Bambusa latiflora)*. Luan van Tot nghiep, Truong Dai Hoc Nong Lam TP. HCM: 51 pp.

Nguyen, T.U. 2001. Bamboo resources in Vietnam. Vietnam Journal of Forest Science (6):1-7.

Nguyen, T.V. 1964. Phong tru moi trong xay dung. Tap San Lam Nghiep (2):26-29.

Nguyen, V.T. 1977. Nghien cuu phong nam muc va bien mau cho nua nguyen lieu giay. Bao Cao Tong Ket KHKT, Vien Cong Nghiep Rung, Ha Noi: 20 pp.

Nordahlia, A.S., Anwar, U.M.K., Hamdan, H., Zaidon, A., Paridah, M.T. and Abd. Razak, O. 2012. Effects of age and height on selected properties of Malaysian bamboo (*Gigantochloa levis*). Journal of Tropical Forest Science 24(1):102-109.

Ota, M. 1955. Studies on the properties of bamboo stem. Part 11: On the Fibre Saturation Point Obtained from the Effect of Moisture Content on the Swelling and Shrinkage of Bamboo Splint. Bulletin of Kyushu University Forestry, Japan (24):61-72.

Pham, N.N. 2006. Establishing process of kiln drying for the bamboo Lo o and the rattan Song may. Research Report No. 11. Department of Science and Technology of Ho Chi Minh-City, Vietnam: 95-102.

Pham, N.N. 2009. Dinh huong su dung mot so loai tre chu yeu trong san xuat thu cong my nghe. De Tai Cap So Khoa hoc va Cong Nghe, TP. HCM: 48pp.

Pham, V.K. 1974. Mot so ket qua nghien cuu buoc dau ve phuong phap bao quan tre dung lam cot dien bang thuoc dau Creozot. Thong Tin KHKT Truong Dai Hoc Lam Nghiep (4):7-19.

Phan, S. 2004. Export of Vietnam bamboo products. Vietnam Non-Timber Forest Products Network (NTFP), NTFP-Newsletter Vol.1: 4-6.

Plank, H.K. 1951. Starch and other carbohydrates in relation to powder post beetle infestation in freshly harvested bamboo. Journal Economic Entomology 44(l):73-75.

Purushotham, A., Sudan, S.K. and Sagar, V. 1953. Preservative treatment of green bamboo under low pneumatic pressure. Bulletin of Indian Forest (178): 121 pp.

Qisheng, Z., Shenxue, J. and Yongyu, T. 2002. Industrial utilization on bamboo. Technical Report No. 26. International Network for Bamboo and Rattan (INBAR), Beijing, China: 207 pp.

Razak, W., Mahmud, S., Tamizi, M. and Awang, A.M.Y. 2006. Durability performance of *Gigantochloa scortechinii* through laboratory fungal decay tests. Research Journal of Microbiology 1:198-202.

Rehman, M.A. and Ishaq, S.M. 1947. Seasoning and shrinkage of bamboo. Indian Forest Records (New Series)-Utilization. Forest Research Institute, Dehra Dun, India 4(2):l-22.

Remadevi, O.K., Muthukrishnan, R., Nagaveni, H.C., Sundararaj, R. and Vijayalakshmi, G. 2005. Durability of bamboos in India against termites and fungi and chemical treatments for its enhancement. In: Paper prepared for the 36th Annual Meeting, 24-28 April 2005, Bangalore, India. International Research Group on Wood Protection. IRG/WP 05-10553: 16 pp.

Sattar, M.A., Kabir, M.F. and Battacharjee, D.K. 1994. Effect of age and height position of muli (*Melocanna baccifera*) and borak (*Bambusa balcooa*) bamboos on their physical and mechanical properties. In: Proceedings of the 4th International Bamboo Workshop Bamboo in Asia and the Pacific, 27-30 November 1991, Chiangmai, Thailand. International Development Research Centre, Ottawa, Canada, and Forestry Research Support Program for Asia and the Pacific, Bangkok, Thailand: 183-187.

Schmidt, O., Wei, D.S., Liese, W. and Wollenberg, E. 2011. Fungal degradation of bamboo samples. Holzforschung 65:883-888.

Sharma, S.G., Tewari, M.C. and Sharsa, R.D. 1972. Chemical seasoning of bamboo in the round for handicrafts. Journal of the Timber Development Association India 13(1):17-23.

Sharma, S.N. 1988. Seasoning behaviour and related properties of some Indian species of bamboo. The Indian Forester 114(10):613-621.

Singh, B. and Tewari, M.C. 1979. Studies on the treatment of bamboo by steeping, open tank and pressure processes. Journal of the Indian Academy of Wood Science 10:68-71.

Smith, N. 2010. Emerging trends for the bamboo industry in Vietnam. Conference on Potential Opportunities for the Vietnam Bamboo Industry, 14 May 2010, Dalat, Vietnam: 5-16.

Sulthoni, A. 1988. A simple and cheap method of bamboo preservation. In: Proceedings of the 3rd International Bamboo Workshop, 14-18 November 1988, Cochin, India: 209-211.

Sulthoni, A. 1989. Bamboo: physical properties, testing methods and means of preservation. In: Bassali, A.V. and Davies, W.G. (Eds.), Proceedings of a Workshop on Design and Manufacturing of Bamboo and Rattan Furniture, 3-14 March 1989, Jakarta, Indonesia: 1-15.

Sulthoni, A. 1996. Shooting period of sympodial bamboo species: an important indicator to manage culm harvesting. In: Ramanuja Rao, I.V. and Widjaja, E. (Eds.), Bamboo, People and the Environment: Propagation and Management. Proceedings of the 5th International Bamboo Workshop, 19-22 June 1995, Ubud, Bali, Indonesia. International Network for Bamboo and Rattan, New Delhi, India 1:96-100.

Sun, F.L., Zhou, Y.Y., Bao, B.F., Chen, A.L. and Du, C.G. 2011. Influence of solvent treatment on mould resistance of bamboo. BioResources 62:2091-2100.

Suprapti, S. 2010. Decay resistance of five Indonesian bamboo species against fungi. Journal of Tropical Forest Science 22:287-294.

Tang, T.K.H. 2009. Bamboo preservation in Vietnam. International Research Group on Wood Protection. IRG/W/40457: 1-11.

Tomalang, F.N., Lopez, A.R., Semara, J.A., Casin, R.F. and Espiloy, Z.B. 1980. Properties and utilization of Philippine erect bamboo. In: Lessard, G. and Chouinard, A. (Eds.), International Seminar on Bamboo Research in Asia. International Development Research Centre and the International Union of Forestry Research Organization, Singapore: 266-275.

Vo, D.P. 2007.Khao sat dac diem cau tao mot so tinh chat co ly cua tre Tam vong. Luan van Tot nghiep, Truong Dai Hoc Nong Lam TP. HCM: 86 pp.

Vu, V.D. 2004. Proposed bamboo species for the five million hectare reforestation program. Vietnam Non-Timber Forest Products Network (NTFP), NTFP-Newsletter Vol.1: 2-4.

Vu, V.D. and Le, V.L. 2005. Ket qua nghien cuu tai nguyen tre nua cua Vietnam. Hoi Nghi: Khoa Hoc Cong Nghe Lam Nghiep 20 Nam Doi Moi (1986-2005) Phan Lam Sinh. Hanoi. Thang 4, 2005: 56-61.

Wang, S.F. 1972. Preventing splitting of bamboo post. Research Report of Department of Forest Products. School of Forestry, Oregon State University: 16 pp.

Wei, D., Schmidt, O. and Liese, W. 2012. Susceptibility of bamboo to fungi. In: Proceedings of the 9th World Bamboo Congress Antwerp, Belgium: 235-245.

Wu, K.T. 1992. The effect of high-temperature drying on the anti-splitting of makino bamboo culm (*Phyllostachys makinoi* Hay.) Wood Science and Technology 26:271-277.

Yosias, G. 2002. Preliminary study on the drying of bamboo (*Bambusa blumeana*) in a wood waste–fired kiln. Bamboo for Sustainable Development. In: Proceedings of the 5th International Bamboo Congress and the 6th International Bamboo Workshop, 2–6 November 1998, San José, Costa Rica. International Network for Bamboo and Rattan, New Delhi, India: 495–510.

Zhou, F.C. 1981. Studies on physical and mechanical properties of bamboo woods. Journal of Nanjing Technology College of Forest Products 2: 32 pp.

6. PUBLICATIONS

6.1 List of peer-reviewed publications

Publication 1

Tang, T. K. H, Schmidt O., Liese W. 2009.
Environment-friendly short-term protection of bamboo against moulding.
Journal of the Timber Development Association of India 55: 8-17.

Publication 2

Tang, T. K. H, Schmidt O., Liese W. 2012.
Protection of bamboo against mould using environment-friendly chemicals.
Journal of Tropical Forest Science 24 (2): 285- 290.

Publication 3

Tang, T. K. H, Liese W. 2011.
Pressure treatment of bamboo culms of three Vietnamese species with boron and CCB preservatives.
Journal of Bamboo and Rattan 10 (1&2): 81-92.

Publication 4

Tang, T. K. H, Welling J., Liese W. 2012.
Investigation on optimisation of kiln drying for the species *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis*.
Bamboo Science and Culture 25: 27-35.

Publication 5

Tang, T. K. H, Welling J., Liese W. 2013.
Kiln drying for bamboo culm parts of the species *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis*.
Journal of the Indian Academy of Wood Science. DOI 10.1007/s13196-013-0089: 6 pp.

6.2 Contributions to the papers

The first author designed, planned, and carried out the experiments in Vietnam and Hamburg. The co-authors contributed to the scientific and technical discussions.

Appendix of five publications

Environment-friendly short-term protection of bamboo against molding

T.K.H. Tang*, O. Schmidt and W. Liese****
*Nong Lam University of Ho Chi Minh City, Vietnam
**Department of Wood Biology, University of Hamburg, Leuschnerstr. 91, 21032 Hamburg, Germany
E-mail: o.schmidt@holz.uni-hamburg.de

Abstract

The protection of the bamboo species *Bambusa stenostachya* and *Thyrostachys siamensis* against molds was investigated with environment-friendly chemicals in the laboratory. Samples were treated with various organic acids and their salts. Mold growth on the specimens was evaluated 1, 2, 4 and 8 weeks after inoculation with a conidia mixture of six molds isolated from bamboos in Vietnam. A second experiment used specimens with the natural flora from the culms and from sample processing. Treatment with 10% acetic acid and 7 % propionic acid, respectively, inhibited mold growth.

Key words: bamboo, molding, short-term protection, environment-friendly organic acids

Introduction

Bamboo in many countries is one of the important vegetative resources as a major raw material and a significant alternative material to wood. Processing and utilization of bamboo often rely on traditional practices, mainly for housing and constructions, furniture making and interior decoration, splits for utilities, agriculture crops, transport, fishing, hunting and household things. In recent years, bamboo became an important material for the industrial manufacturing of round and laminated furniture, parquet and pulp for worldwide export.

Bamboo has a low natural durability against fungi and insects compared to wood (Liese and Kumar 2003). Therefore, the service life of bamboo structures is often short. Tropical climates with high temperature and humidity favor molds and insects. Generally, several fungi from the groups of deuteromycetes (molds), ascomycetes and basidiomycetes effect diseases of the growing bamboo (Mohanan and Liese 1990, Morakotkarn et al. 2007) and affect also the harvested culms (Mohanan 1997, 2008, Ma et al. 2009a). Molds occur at the cross-ends and on the surface of culms in a humid atmosphere as they require high relative humidity above 70%. Especially, bamboo material during storage, processing, transport in container and in its final use is affected by molds (Liese and Kumar 2003).

For protection of wood and bamboo against molds and other fungi, pentachlorophenol had been widely used. However, pentachlorophenol is now banned due to its high toxicity in many parts of the world (Tang 2009). Therefore, bamboo manufacturers have pressing problems to protect bamboo for home use and export. Since bamboo countries export large quantities of culms in containers the damage due to mold growth has become quite serious. Plate 1 shows molded culms at arrival in Hamburg harbour after container transport from Vietnam. Manufacturers greatly need cost-effective and also environment-friendly treatment methods for moist bamboo during its susceptive phase. Seasoned, dry bamboo will not be damaged by fungi.

Welling and Lambertz (2008) used chemicals of alkaline pH value in order to reduce molding of pine sap wood specimens and obtained protection with potassium and sodium carbonate. Liese and Walter (1978) showed the efficacy of an acid formulation (boric acid) for the protection of sugar cane bagasse against molding. The protective efficacy of organic acids like acetic, boric, citric, formic, propionic and sorbic acid has been applied since long for food and as antiseptica (Wallhäußer and Schmidt 1967). For short-term protection against molding, our emphasis was on the use of free acids whereby the preventing effect of acids was combined with the additional protective effect of their low pH-value against microorganisms (Schmidt 2006). Ma et al. (2009b) showed inhibition of molds from bamboo by tebuconazole, prochloraz and fluodioxonil in agar tests.

Materials and methods

Bamboo specimens

Bambusa stenostachya Hackel and *Thyrostachys siamensis Gamble* are two important bamboo species of Vietnam. They are used for housing and for production of furniture mainly to export (Phan 2004). Ten mature bamboo culms of 3 - 4 years age of each species were collected from a plantation in Tay Ninh province, South Vietnam. From the fresh culms, samples of 70 mm length were taken halfway between the internodes and longwise split. Their moisture content was 100 to 120 %.

Chemicals

Acetic, boric , citric , formic , propionic, sorbic acid, and the salts potassium citrate, sodium acetate, sodium borate and sodium propionate from laboratory providers were applied in various formulations (Table 1).

Fungi

The six molds used were isolated from bamboos at the Nong Lam University of Ho Chi Minh City, Vietnam. Identification by DNA-ITS sequencing as described by Schmidt (2000) revealed Aspergillus niger, A. flavus, A. oryzae, Aspergillus sp., Paecilomyces variotii and Penicillium sp.

Treatment, inoculation and incubation

Two specimens of each bamboo species were dipped 5 min. in the respective treatment solution and placed in a small plastic box 10 x 10 x 6 cm (Plate 2). Specimens were not sterilized before incubation. For one test series, artificial infection with a water-based mixture of conidia of the six molds was done with a small brush. The other series contained only the natural mold flora from the culms and from the samples processing. To avoid drying of the specimens during culture, the boxes were completely closed, so that a shortage of oxygen might be considered, although the air volume of over 500 cm^3 should have been sufficient for the relatively few mold hyphae living on the small specimens. Incubation at 30°C and 75% RH lasted 1, 2, 4 and 8 weeks.

Assessment of mold growth

The development of mold growth on the surface of the bamboo specimens was assessed according to the rating in Table 2. The scheme values the percentage of the surface covered with molds or other staining fungi (British Standard Institution 2005).

Results and discussion

Plate 3 shows the effective and ineffective treatments of the series `artificial infection´. The treatments with 10% acetic acid (formulation 2), propionic acid (formulations 7 and 8) as well as with the mixture of 3% boric acid and 7% propionic acid (formulation 21) totally prevented mold growth over the whole incubation period of 8 weeks.

The results of both test series are summarized in Table 3. Some differences occurred within the first two weeks, the inoculated specimens being faster overgrown due to high amount of spores in the inoculum. After 8 weeks, there were no significant differences in final molding between the series `artificial infection´ and `natural mold flora´.

Ten percent acetic acid, 7% propionic acid and the boric/propionic acid mixture prevented mold growth in both series completely. All other treatments led to severe (rating 3) or very severe (rating 4) mold growth. Both bamboo species behaved rather similar regarding mold susceptibility and prevention. As exception, formulation 18 (boric acid/acetic acid), showed molded *T. siamensis* and clean *B. stenostachya* specimens.

Acetic acid belongs to the oldest and most widely used preservatives for meat, fish and fruits. The protecting effect against many bacteria, yeasts and molds is mainly due to the acid pH value. Propionic acid and her salts particularly affect fungi and have been used for bread, jam and cheese (Wallhäußer and Schmidt 1967). Dipping fresh boards from the light African Ilomba (*Pycnanthus angolenis* Exell) in a solution of each 5% propionic and formic acid almost completely prevented the brown discoloration by bacteria (Schmidt 2006). Boric acid is applied as antisepticum in eye/nose drops and ointments and was used for egg-based food (Wallhäußer and Schmidt 1967).

The effective formulations had pH-values between 2.8 and 3.0: 10% acetic acid (pH 2.8, treatment 2) and propionic acid (pH 2.8/2.9, treatments 7 and 8). Their salts 10% sodium acetate (pH 8.5, no. 11) and sodium propionate (pH 8.0/8.5, nos. 11/12) had no protective effect.

The effect of the boric acid/propionic acid (treatment 21) could be entirely due to propionic acid, as propionic acid alone (no. 7) prevented moulding. A similar trend occurs for the boric acid/acetic acid (no. 18) due to acetic acid (no. 1), although treatment 18 was better than 7% acetic acid alone (no. 1). Boric acid was included in the tests, as boron containing compounds are the most widely used preservatives for bamboo protection against a variety of fungi as well as for borers (Liese and Kumar 2003). Since boric acid alone was not tested, it is difficult to assess the pure boric acid effect. The pH value of a 4 % boric acid solution is around 4.

For the laboratory experiments, only one infection of the specimens was done. Under intended field conditions with larger samples, bamboo will be exposed to permanent infection pressure from the surrounding air, so that the applied concentrations might not meet those conditions.

The tested chemicals do not fix to the bamboo culm. Washing out by rain reduce their protective efficacy (Willeitner and Liese 1992). For practical use, the treated material must be protected from rain.

Conclusions

The laboratory experiments have shown that molding of bamboo can be prevented by simple treatment with environment-friendly chemicals. Results revealed that dipping into acetic acid and propionic acid prevented mold growth for 2 months. Other chemicals tested were less effective or ineffective. The protection is related to the pH value of the treatment solution, as the free acids acetic and propionic acid have protective effect, but not their salts.

Experiments with the effective formulations will be continued under field conditions in Vietnam with larger bamboo dimensions, like round and split culms, as well as handicrafts and commodities. Since molding of bamboo is a serious devaluation in trade, corresponding experiments are recommended for other bamboo countries with their respective species.

References

British Standard Institution (2005). Wood preservatives Determination of the preventive effectiveness against sapstain and mould fungi on freshly sawn timber Field test. DD CEN/TS 15082; cited from *Welling and Lambertz 2008.*

Liese, W. and S. Kumar (2003). Bamboo Preservation Compendium, International Network Bamboo and Rattan, INBAR Techn. Rep. 22, Beijing.

Liese, W. and K. Walter (1978). Deterioration of bagasse during storage and its prevention. Proc. 4th International Symposium, Berlin, pp. 247-250.

Ma, X., M. Jiang, and D. Qin (2009a). Isolation and identification of stain fungi and mould fungi on bamboo wood in China. *Intern. Res. Group Wood Preserv.* IRG/WP/ 10703: 1-14.

Ma, X., A. Sun, M. Jiang and D. Qin (2009b) Laboratory test of some formulations against stain and mould fungi isolated from bamboo wood. *Intern. Res. Group Wood Preserv.* IRG/WP/30508: 1-6.

Mohanan, C. (1997). Diseases of bamboos in Asia. International Network Bamboo and Rattan, INBAR Techn. Rep. 10, Beijing.

Mohanan, C. (2008). Culm, foliage, rhizome, root and inflorescence diseases of bamboos in Kerala, India and their management. *J. Bamboo Rattan* 7: 251-269.

Mohanan, C. and W. Liese (1990). Diseases of bamboos. Int. *J. Tropical Plant Diseases* 8: 1-20.

Morakotkarn, D., H. Kawasaki, and T. Seki (2007). Molecular diversity of bamboo-associated fungi isolated from Japan. *FEMS Microbiol. Lett.* 266: 10-19.

Phan, S. (2004). Export of Vietnam bamboo products. Vietnam-Non Timber Forest Products Network - NTFP *Newsletter* 1: 4-6.

Schmidt, O. (2000). Molecular methods for the characterization and identification of the dry rot fungus *Serpula lacrymans. Holzforschung* 54: 221-228.

Schmidt, O. (2006). Wood and tree fungi. Biology, damage, protection and use. Springer, Berlin, Heidelberg, New York.

Tang, T.K.H. (2009). Bamboo preservation in Vietnam. *Intern. Res. Group Wood Preserv.* IRG/WP/40457: 1-11.

Wallhäußer, K.H. and H. Schmidt (1967). Sterilisation, Desinfektion, Konservierung, Chemotherapie. Thieme-Verlag, Stuttgart.

Welling, W. and G. Lambertz (2008). Environmentally friendly temporary anti-mould treatment of packaging material before drying. Maderas. Ciencia y tecnología 10: 25-33.
Willeitner, H. and W. Liese (1992). Wood Protection in Tropical Countries. Technical Cooperation Fed. Rep. Germany (GTZ), Eschborn.

Table-1. Acids and salts used for anti-mold test

Formulations	Acid / salt	Concentration (%)	pH –value
1	acetic acid (AA)	7	3.0
2		10	2.8
3	citric acid (CA)	7	2.7
4		10	2.6
5	formic acid (FA)	7	3.8
6		10	3.7
7	propionic acid (PA)	7	2.9
8		10	2.8
9	sorbic acid (SA)	0.6	3.7
10	Na-acetate (NA)	7	8.4
11		10	8.5
12	Na-propionate (NP)	7	8.0
13		10	8.1
14	boric acid (BA)+Na-borate (BS)	2% BA + 3% BS	8.7
15	BA + NP	3% BA + 7% NP	7.0
16	BA + NC	3% BA + 7% NC	7.9
17	BA + K-citrate(KC)	3% BA + 7% KC	8.3
18	BA + AA	3% BA + 7% AA	3
19	BA + SA	3% BA + 0.3% SA	3.9
20	BA + CA	3% BA + 7% CA	2.5
21	BA + PA	3% BA + 7% PA	3.0
Control	H_2O	-	-

Table-2. Rating scheme for determining mold growth on bamboo specimens

Rating	Description	Definition
0	no coverage	no growth
1	1-10 % coverage	slightly overgrown
2	11-25 % coverage	moderately overgrown
3	26-50 % coverage	severely overgrown
4	>50 % coverage	very severely overgrown

Plate 1. Molded bamboo culms in Hamburg after container transport from Vietnam

Plate 2. Specimens in plastic boxes for mold protection test.

Table-3. Efficacy of anti-mold treatments (cf. Table 2)

Bamboo species	**Incubation time (weeks)**															
	1				**2**				**4**				**8**			
	Ts		**Bs**		**Ts**		**Bs**		**Ts**		**Bs**		**Ts**		**Bs**	
Test series	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Formulation 1	0	0	0	0	1	0	0	0	4	0	3	0	4	3	4	3
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	1	4	3	4	4	4	4	4	4	4	4	4	4	4	4
4	2	0	4	4	4	3	4	4	4	4	4	4	4	4	4	4
5	4	1	4	2	4	4	4	4	4	4	4	4	4	4	4	4
6	4	2	3	4	4	4	4	4	4	4	4	4	4	4	4	4
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	2	0	4	3	4	3	4	4	4	4	4	4	4	4
10	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
11	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
12	0	0	2	0	3	1	4	3	4	4	4	4	4	4	4	4
13	0	0	1	0	4	1	4	4	4	4	4	4	4	4	4	4
14	0	0	3	3	4	2	4	4	4	4	4	4	4	4	4	4
15	0	0	0	0	3	1	4	1	4	4	4	4	4	4	4	4
16	1	1	3	1	4	3	4	4	4	4	4	4	4	4	4	4
17	1	0	3	2	4	3	4	4	4	4	4	4	4	4	4	4
18	0	0	0	0	0	0	0	0	1	0	0	0	3	2	0	0
19	2	0	2	0	4	2	4	3	4	4	4	4	4	4	4	4
20	2	0	2	2	4	4	4	4	4	4	4	4	4	4	4	4
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Control	3	0	3	0	4	3	4	3	4	4	4	4	4	4	4	4

Ts =*Thyrostachys siamensis*, Bs = *Bambusa stenostachya*, A = artificial infection, B = natural mold flora

Plate 3. Artificially infected and differently treated bamboo specimens after 8 weeks of incubation.

Journal of Tropical Forest Science 24(2): 285–290 (2012)

PROTECTION OF BAMBOO AGAINST MOULD USING ENVIRONMENT-FRIENDLY CHEMICALS

TKH Tang[1, 2, *], O Schmidt[1] & W Liese[1]

[1]*Centre for Wood Science, University Hamburg, Leuschnerstr 91, D 21031 Hamburg, Germany*
[2]*Faculty of Forestry, Nong Lam University of HCM, Thu Duc-District, Ho Chi Minh City, Vietnam*

Received September 2011

TANG TKH, SCHMIDT O & LIESE W. 2012. Protection of bamboo against mould using environment-friendly chemicals. The protection of the bamboo species *Bambusa stenostachya, Bambusa procera, Dendrocalamus asper* and *Thyrostachys siamensis* against moulds was tested with environment-friendly chemicals under practical conditions. Bamboo samples were treated with several organic acids. Mould growth on the specimens was evaluated 1, 2, 4 and 8 weeks after exposure at the storage site of the Bamboo Nature Company, Binh Duong province, South Vietnam. Treatments with 10% acetic acid and 7% propionic acid completely inhibited mould growth on *B. stenostachya* and *T. siamensis*. For full protection of *B. procera* and *D. asper*, 10% propionic acid was needed.

Keywords: Field test, antimould treatment, organic acids

TANG TKH, SCHMIDT O & LIESE W. 2012. Perlindungan buluh terhadap kulapuk jangka pendek menggunakan bahan kimia mesra alam. Perlindungan buluh *Bambusa stenostachya, Bambusa procera, Dendrocalamus asper* dan *Thyrostachys siamensis* terhadap kulapuk diuji di lapangan menggunakan bahan kimia mesra alam. Sampel buluh dirawat dengan beberapa asid organik. Pertumbuhan kulapuk dinilai pada minggu pertama, kedua, keempat dan kelapan selepas pendedahan di tapak simpanan Syarikat Bamboo Nature, daerah Binh Duong, Selatan Vietnam. Rawatan dengan 10% asid asetik dan 7% asid propionik menghalang sepenuhnya pertumbuhan kulapuk pada *B. stenostachya* dan *T. siamensis*. Perlindungan penuh bagi *B. procera* dan *D. asper* dicapai apabila 10% asid propionik digunakan.

INTRODUCTION

In many tropical countries, bamboo is one of the important vegetative resources after plantation wood and is a major raw material for the forest product industry. In recent years, bamboo has become the main material for industrial manufacturing of round and laminated bamboo furniture and parquet. It is also widely exported as bamboo culms.

Bamboo has low natural durability against fungi and insects compared with wood (Liese 1998). In general, several fungi from the groups of deuteromycetes (moulds), ascomycetes and basidiomycetes colonise the culms of bamboos (Mohanan 1997). Tropical climate with high temperatures and relative humidity above 70% facilitate mould growth. Exposed bamboo is especially affected by moulds during storage, processing, transport in containers and its final use (Liese & Kumar 2003). Moulds grow on the surface and at the cross-ends of culms.

Pentachlorophenol had been widely used for protection of bamboo against moulds and other fungi. However, the chemical is banned in many parts of the world due to its high toxicity (Tang 2009). Thus, bamboo manufacturers have extreme problems in protecting bamboo for local use and export. Since bamboo countries export large quantities of bamboo culms and utilities in containers, the damage due to mould growth at port arrival has become quite serious. Manufacturers need cost-effective and also environment-friendly treatment methods for moist bamboo during its susceptible phase.

Hydrocloric acid has been shown to provide good protection for bamboo compared with sodium hydroxide (Sun et al. 2011). The effectiveness of the acid led us to investigate various organic acids, namely, acetic, boric, citric, formic, propionic and sorbic acids against moulds of bamboo. These acids have

*E-mail: tang@holz.uni-hamburg.de

long been used for food protection and as antiseptics. Suitable concentrations for food are 0.03 to 4% (Wallhäußer & Schmidt 1967). Previous laboratory experiments have shown that moulding of bamboo can be prevented by simple treatment with the above environment-friendly acids in concentrations from 7 to 10% (Tang et al. 2009).

To test the functionality of the acids, field tests under practical conditions were carried out at the Bamboo Nature Company, Binh Duong province of South Vietnam. We investigated the mould susceptibility of four bamboo species— *Bambusa stenostachya*, *Bambusa procera*, *Dendrocal-amus asper* and *Thyrostachys siamensis*—which are important in South Vietnam and widely used for production of structures, furniture and export (Phan 2004).

MATERIALS AND METHODS

Mature 3-year-old bamboo culms from *B. stenostachya*, *B. procera*, *D. asper* and *T. siamensis* were collected from a bamboo plantation at the Bamboo Nature Company. They were harvested in June, July and September 2009. Samples were prepared from the fresh culms either as culm parts or splits of 120 and 60 cm in length respectively. In both cases, the epidermis was removed by sanding. These forms of samples were the most common for production of furniture in Vietnam. The moisture content was 100 to 120%. Samples were prepared in seven replicates for each treatment.

Effective chemicals (namely, citric, formic and sorbic acids) from previous laboratory experiments (Tang et al. 2009), acetic, boric and propionic acids, and the concentrations used are shown in Table 1. In the previous experiment, sample size was smaller compared with the current experiment. Therefore, instead of 3 min used previously, bamboo specimens in this experiment were dipped for 10 min in the treatment solution. In both cases, only the outer layers of the samples became impregnated. Samples were then bundled and placed on supports over wet soil ground (Figure 1). After 1 day of exposure to natural infection, samples were covered with plastic sheet to avoid sunlight and drying (Figure 1). The test was carried out in a roof-covered raw material storage area in the factory of the Bamboo Nature Company. It was known that the storage space suffered from severe mould contamination from an area underneath the ground floor which experienced high humidity produced by water evaporation from uncovered ground soil.

The tests were carried out in three periods, each of 8 weeks during the rainy season in 2009 (June–August, July– September and September–November). The temperature during exposure was about 28 °C and the relative humidity, between 80 and 90%.

The development of mould growth on the surface of the specimens was assessed according to the rating scheme given in Table 2 (British Standard Institution 2005). The visual evaluation of damage was rated after 1, 2, 4 and 8 weeks.

RESULTS AND DISCUSSION

Results of the experiments for the four study bamboo species are summarised in Tables 3 to 6. Differences occurred in moulding between exposure periods. In most treatments, specimens from the second period were more quickly overgrown by moulds due to the high relative humidity of about 90%.

There were significant differences in efficacy of antimould treatments for the bamboo species. Treatment with 10% propionic acid prevented mould growth on all four bamboo species during the whole exposure period of eight weeks. Ten

Table 1 Organic acids used in the investigation

Chemical	pH
10% acetic acid	2.8
7% propionic acid	2.9
10% propionic acid	2.8
3% boric acid + 7% acetic acid	3.0
3% boric acid + 7% propionic acid	3.0
Water (control)	Not determined

Figure 1 Bundled specimens on supports over wet soil ground and covered for infection

Table 2 Rating scheme for determining mould growth on bamboo specimens

Rating	Description	Definition
0	No coverage	No growth
1	1–10% coverage	Slightly overgrown
2	11–25% coverage	Moderately overgrown
3	26–50% coverage	Severely overgrown
4	> 50% coverage	Very severely overgrown

Table 3 Efficacy of antimould treatments for *Bambusa stenostachya*

Organic acid	Period*	Exposure time							
		1 week		2 weeks		4 weeks		8 weeks	
		C	S	C	S	C	S	C	S
Acetic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 7%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Boric acid 3% + acetic acid 7%	I	0	0	0	0	0	0	0	0
	II	1	1	1	1	2	2	1	2
	III	0	2	2	2	2	2	2	2
Boric acid 3% + propionic acid 7%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Control	I	1	2	2	3	2	3	2	3
	II	2	3	3	4	3	4	3	4
	III	1	3	3	3	3	3	4	4

*Test period in 2009, each lasting eight weeks: I = June–August, II = July–September, III September–November; C = culm parts, S = split parts

Journal of Tropical Forest Science 24(2): 285–290 (2012) *Tang TKH et al.*

Table 4 Efficacy of antimould treatments for *Bambusa procera*

Organic acid	Period*	Exposure time							
		1 week		2 weeks		4 weeks		8 weeks	
		C	S	C	S	C	S	C	S
Acetic acid 10%	I	1	2	1	2	2	2	2	2
	II	2	3	3	4	3	4	3	4
	III	1	2	2	2	2	3	2	3
Propionic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 7%	I	1	1	1	2	1	2	2	2
	II	1	2	2	3	3	3	3	3
	III	1	2	1	2	1	2	2	2
Boric acid 3% + acetic acid 7%	I	2	3	4	4	4	4	4	4
	II	3	4	4	4	4	4	4	4
	III	1	3	3	3	3	3	3	3
Boric acid (3%) + propionic asid 7%	I	0	0	1	1	1	1	1	1
	II	1	1	2	2	2	2	2	2
	III	1	1	1	1	1	1	1	1
Control	I	2	3	3	3	3	3	3	3
	II	4	4	4	4	4	4	4	4
	III	3	4	3	4	3	4	3	4

*Test period in 2009, each lasting eight weeks: I = June–August, II = July–September, III September–November; C = culm parts, S = split parts

Table 5 Efficacy of antimould treatments for *Dendrocalamus asper*

Organic acid	Period*	Exposure time							
		1 week		2 weeks		4 weeks		8 weeks	
		C	S	C	S	C	S	C	S
Acetic acid 10%	I	1	2	1	2	2	2	2	2
	II	2	3	3	4	3	4	3	4
	III	1	2	2	2	2	3	2	3
Propionic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 7%	I	1	1	1	2	1	2	2	2
	II	1	2	2	3	3	3	3	3
	III	1	2	1	2	1	2	2	2
Boric acid 3% + acetic acid 7%	I	2	3	4	4	4	4	4	4
	II	3	4	4	4	4	4	4	4
	III	1	3	3	3	3	3	3	3
Boric acid (3%) + propionic acid 7%	I	0	0	1	1	1	1	1	1
	II	1	1	2	2	2	2	2	2
	III	1	1	1	1	1	1	1	1
Control	I	2	3	3	3	3	3	3	3
	II	4	4	4	4	4	4	4	4
	III	3	4	3	4	3	4	3	4

*Test period in 2009, each lasting eight weeks: I = June–August, II = July–September, III September–November; C = culm parts, S = split parts

Table 6 Efficacy of antimould treatments for *Thyrostachys siamensis*

Organic acid	Period*	Exposure time							
		1 week		2 weeks		4 weeks		8 weeks	
		C	S	C	S	C	S	C	S
Acetic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 10%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Propionic acid 7%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Boric acid 3% + acetic acid 7%	I	0	1	1	2	1	2	1	2
	II	1	1	2	3	2	3	3	3
	III	0	2	2	2	2	3	3	3
Boric acid 3% + propionic acid 7%	I	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0
	III	0	0	0	0	0	0	0	0
Control	I	1	2	2	3	2	3	2	3
	II	2	3	3	4	3	4	3	4
	III	1	3	3	3	3	3	4	4

*Test period in 2009, each lasting eight weeks: I = June–August, II = July–September, III September–November; C = culm parts, S = split parts

per cent acetic acid, 7% propionic acid and the boric/propionic acid mixture prevented complete mould growth during all exposure periods in *B. stenostachya* and *T. siamensis*, but not in *B. procera* and *D. asper*. Generally, results of this field test are similar to our previous laboratory experiments with smaller samples (Tang et al. 2009). There were also differences among bamboo species with regard to the degradation by rot fungi (Schmidt et al. 2011). Further experiments regarding mould susceptibility of different bamboo species may be of interest.

The effective acid solutions had acidic pH values between 2.8 and 3.0. Our previous laboratory tests proved that only solutions with acidic pH were effective, namely, the free acids (Tang et al. 2009). Their salts with alkaline pH values were less or not effective. For example, acetic acid inhibited moulds but sodium acetate did not. This meant that the preserving function of a solution was mainly due to its acidity. Propionic acid had also protected sugar cane bagasse from moulding (Liese & Walter 1978) and prevented ilomba wood from bacterial staining (Schmidt 2006).

A possible disadvantage of the dipping procedure with organic acids may be that the acid solutions are not durable. In view of repeated use of the dipping solution, propionic acid, for example, was oxidised to acetic acid, carbon dioxide and water. Thus, fresh acid solutions should be used always. Corrosion of the dipping containers must also be considered, if made from iron. More importantly, the acids do not fix to the bamboo tissue and are washed out by rain. The bamboos are only protected during the short storage period. It is also important to ensure that the susceptible phase of bamboo drying after dipping is performed in a roof-covered area.

This investigation has shown that bamboos can be protected from moulding at least during the critical period after harvest. The non-poisonous and environmental-friendly organic acids used in this study, especially 10% propionic acid, were effective in inhibiting mould growth. Their effectiveness was mainly due to their acidity. The proposed method is economical because the costs of the acids are acceptable, i.e. Europe: €80/t and NAFTA, Asia: USD130/t according to BASF Chemical Company.

Further investigations should deal with the possible consequences of the treatment for subsequent bamboo use in long-term service, including influence on colour, smell and gluing ability of parquets.

ACKNOWLEDGEMENTS

We would like to thank the Bamboo Nature Company, Binh Duong province, Vietnam for providing facilities and materials for the project. We acknowledge the assistance of Ho Thuy Dung, Nguyen Minh Hien and Vu Thi Lam An, researchers and lecturers of Nong Lam University and also staff of the Bamboo Nature Company during the field experiments.

REFERENCES

British Standard Institution. 2005. *Wood Preservatives: Determination of the Preventive Effectiveness Against Sapstain and Mould Fungi on Freshly Sawn Timber—Field Test. DD CEN/TS 15082*. British Standard Institution, London.

Liese W. 1998. The anatomy of bamboo culms. *INBAR Technical Report* 18: 156–158.

Liese W & Kumar S. 2003. Bamboo preservation compendium. *INBAR Technical Report* 22: 41–46.

Liese W & Walter K. 1978. Deterioration of bagasse during storage and its prevention. Pp 247–250 in *Proceedings of the Fourth Biodeterioration Symposium*. 28 August–1 September 1978, Berlin.

Mohanan C. 1997. *Diseases of Bamboos in Asia*. International Development Research Centre, New Delhi.

Phan S. 2004. Export of Vietnam bamboo products. *Vietnam Non Timber Forest Products Network (NTFP) Newsletter* 1: 4–6.

Schmidt O. 2006. *Wood and Tree Fungi. Biology, Damage, Protection, and Use*. Springer Press, Berlin.

Schmidt O, Wei DS, Liese W & Wollenberg E. 2011. Fungal degradation of bamboo samples. *Holzforschung* 65: 883–888.

Sun FL, Zhou YY, Bao BF, Chen AL & Du CG. 2011. Influence of solvent treatment on mould resistance of bamboo. *BioResources* 62: 2091–2100.

Tang TKH. 2009. Bamboo preservation in Vietnam. Pp 1–11 in *Documents of the 40th Conference of International Research Group on Wood Protection*. 24–28 May 2009, Beijing.

Tang TKH, Schmidt O & Liese W. 2009. Environment-friendly short-term protection of bamboo against molding. *The Timber Development Association of India* 55: 8–17.

Wallhäußer KH & Schmidt H. 1967. *Sterilisation, Desinfektion, Konservierung, Chemotherapie*. Thieme Press, Stuttgart.

J. Bamboo and Rattan, Vol.10, Nos. 1&2, pp. 81-92 (2011)

Pressure treatment of bamboo culms of three Vietnamese species with boron and CCB preservatives

Thi Kim Hong Tang[1, 2], Walter Liese[1]
[1] *Department of Wood Science, University Hamburg, Leuschnerstr. 91, D 21031 Hamburg, Germany*
[2] *Faculty of Forestry, Nong Lam University of Ho Chi Minh City, Linh Trung Ward, Thu Duc-District, Ho Chi Minh City, Vietnam*

Abstract: Culms of three common Vietnamese bamboo species, *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis*, were pressure-impregnated using various schedules for obtaining adequate retention. Two preservatives were applied: a mixture of borax and boric acid (BB) and a mixture of sodium dichromate, copper sulphate and boric acid (CCB). Culm parts from the bottom and middle section were investigated at two moisture levels with pressures of 2.5, 4.0, 5.5, 7.0 and 8.5 bar for 60, 90 and 120 minutes, respectively. The penetration and retention of the preservatives were evaluated to arrive the appropriate schedule. For indoor use with a retention of 4 kg/m^3 BB, *T. siamensis* needs a pressure of 4 bar for 60 minutes, the bamboos *B. stenostachya* and *D. asper* a pressure of 5.5 bar for 60 minutes. For outdoor application with a retention of 10 kg/m^3 CCB, *T. siamensis* requires 5.5 bar for 120 minutes, but *B. stenostachya* 7 bar pressure for 60 minutes, and *D. asper* for 120 minutes.

Keywords: Bamboo culms, pressure treatment, efficient schedules.

INTRODUCTION

Bamboo culms are susceptible to insect and fungal attack and will be deteriorated with time, thus limiting their use for constructions and long-lasting products. The protection of bamboo is essential for extending its durability and service life. To obtain sufficient protection, different preservative methods are followed of which the pressure method is the most effective one. It provides fast production of treated culms on a large scale (Liese and Kumar, 2001).

In Vietnam, the export of bamboo products has recently increased. According to the Department of Foreign Trade 2009, bamboo furniture is one of the lead products for export on a large scale. Manufactures generally adopt the vacuum pressure impregnation following one schedule for all bamboo species (Tang, 2009). The method applied does not consider the different properties of bamboo species, the preservative and the treatment schedule. An improper treatment, as low pressure may limit the required preservative up-take, whereas a high pressure can cause cracks and collapses (Kumar *et al*., 1994). Hence, it is necessary to evaluate the pressure treatment used for the species.

In South Vietnam, *Bambusa stenostachya* (Tre Gai), *Dendrocalamus asper* (Manh Tong) and *Thyrsostachys siamensis* (Tam Vong) are the important commercial bamboos for furniture and export. Therefore, treatment schedules by pressure process were investigated for these species.

MATERIALS AND METHODS

The sample preparation and the investigation of the various treatment schedules were carried out in 2010 and 2011 at the factory of the Bamboo Nature Company, Binh Duong province and at the Faculty of Forestry, Nong Lam University, Vietnam. A detailed working plan and the treatment parameters were outlined before and the treated samples were sent to the Department of Wood Science, University Hamburg, Germany, for further analytical investigations.

Material

The experimental material of 3-year old culms was extracted from a 10-year old plantation in the Binh Thuan province, South Vietnam. Culms of *T. siamensis* with 9 m length, *B. stenostachya* and *D. asper* with 12 m length were cut 25 cm above ground. Culm parts of 120 cm length were taken representing the bottom and middle portion, as shown in Fig. 1. For each test, nine samples were used with a total of 540 culm parts for each of the three species.

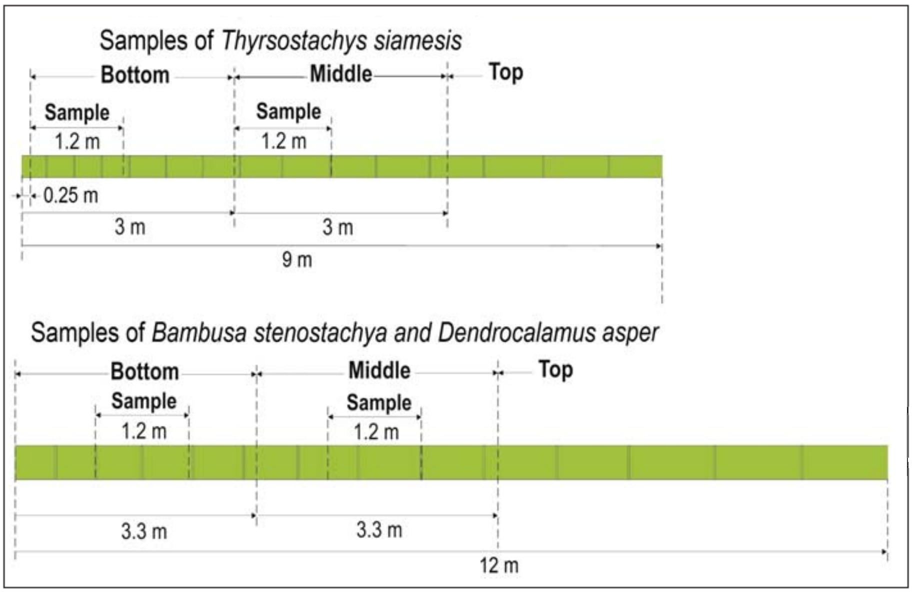

Figure 1. Location of the samples

For the cavity species, *B. stenostachya* and *D. asper*, the diaphragm was fractured by a 1 cm stick. The material was first air-dried under shade for about 5 weeks. Then, the skin was removed by machine sanding as a usual procedure in Vietnam for furniture making (Fig. 2, 3). Further information of the samples tested is given in Table 1.

Figure 2. Skin removal by sanding, Co. Bamboo Nature

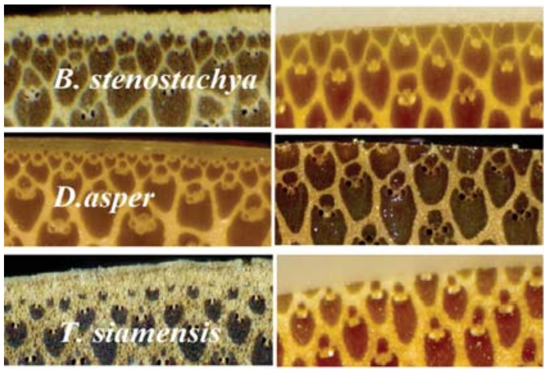

Figure 3. Cross-sectional view before and after skin removal

Table 1. Structural features of the samples tested

Bamboo species	Culm position	Culm diameter (mm)	Wall thickness (mm)	Internode length (cm)	No. of nodes
T. siamensis	bottom	43	solid	18	6
	middle	35	12	28	4
B. stenostachya	bottom	81	16	27	4
	middle	70	10	36	3
D. asper	bottom	86	17	29	4
	middle	72	11	41	3

Influence of moisture content

The influence of the moisture content was investigated for two ranges, 30 - 40% and 15 - 20%, whereby the samples after air drying were placed in an air conditioning room for two, three weeks respectively.

Preservatives

Two treatment solutions were tested: for indoor furniture 6% BB as mixture of borax and boric acid (1.5: 1 ratio), for outdoor structures 6% CCB containing sodium dichromate, copper sulphate and boric acid (4:3:1.5 ratio).

Impregnation cylinder

The experiments were conducted in a vacuum pressure cylinder of 40 cm in diameter and 140 cm in length. After each treatment**,** the solution was changed to ensure the same concentration.

Treatment schedules

For all impregnation schedules an initial vacuum of 600 mm Hg for 30 minutes and a final vacuum of 600 mm Hg for 15 minutes were applied. Five pressures of 2.5, 4.0, 5.5, 7.0 and 8.5 bar were used, each of them for 60, 90 and 120 minutes. Thus, in total 15 impregnation schedules were tested.

Determination of preservative uptake

The preservative retention was determined by weighing the samples before and after impregnation. The uptake was calculated as R = (A x C: 100) : V, with A as liquid absorption = final weight - initial weight; C as solution concentration and V as volume of the sample. To obtain the mean retention, the results from the nine samples of each test were averaged.

The radial depth of penetration was measured on a cross-section at the middle of the sample. The penetration was identified with staining by curcuma for boron in BB and by chrome azurol for copper in CCB. The reagents indicate BB by red color and CCB by dark blue. For each test, three replicates of the nine samples were investigated and the penetration was classified in five grades (Table 2).

Table 2. Classification of preservative penetration

Grade	Penetration of the culm wall
0	No penetration
1	<25%
2	25-50%
3	50-75%
4	>75% - complete

For determining the gradient of absorption within the culm part, 5 cm long specimens from both ends and the middle part of the sample and also the outer, central and inner layers of the middle part were investigated. From the nine samples of each test, five replicates were taken. The retention of BB and CCB was determined by analyzing the copper, chromium and boron content using the Inductively Coupled Plasma (ICP) method.

Data analysis

The data were statistically analyzed using Excel 2007 and Minitab. The differences between mean values of retention for the species, culm portion, moisture range, preservative and the treatment schedule were evaluated by means of the F-test. The regression equation of the retention with pressure and time was established by ANOVA.

RESULTS AND DISCUSSION

Penetration

The results of the preservatives penetration into the culm part are presented in Table 3**.** With a pressure of 2.5 bar, only the middle sample of *T. siamensis* had full penetration with grade 4. The bottom part of *T. siamensis* as well as both parts of *B. stenostachya* and *D. asper* obtained the low grades 1 and 2. By raising the pressure to 4 bar the penetration for the three bamboos increased to the grades 3 and 4. Pressures of 5.5 bar and higher resulted generally in the grade 4.

Retention

The preservative absorption of the three species treated with BB and CCB by pressures from 2.5 to 8.5 bar for three periods is summarized in Tables 4 a, b. Statistical analysis showed a highly significant effect of the species, culm portion, moisture content, preservative as well as of the pressure and time applied for the retention (Table 4 c).

Absorption by the species

Between the three species, significant differences existed in the preservative retention. *T. siamensis* had the highest uptake, followed by *B. stenostachya* and *D. asper.* This is due to the different structural features. According to Hoang *et al.* (2007), the oven-dried density of *T. siamensis* ranges from 0.41- 0.46 g/cm^3, of *B. stenostachya* from 0.65-0.72 and of *D. asper* from 0.71- 0.78. Thus, a lower specific gravity and thinner walls (Table 1) result in a higher absorption**.** An investigation on the structural features causing these differences would be worthwhile.

Preservative uptake by the culm portion

For all species, the middle part of the culms showed a higher absorption than the bottom one. Such relation was also found by Kumar *et al.* (1992), Nguyen (2005) and Wahab *et al*. (2005). Although the specific gravity is higher in the middle part than in the bottom, its culm wall is thinner and contains more vascular bundles (Grosser and Liese, 1971; Liese, 1998).

Effect of moisture content

The influence of the two moisture ranges on the preservative uptake was statistically significant (Table 4 c). At all pressures applied, samples with 15 - 20% moisture had about 15% more absorption than at 30 - 40%.

Table 3. Classification of the penetration of the three bamboo species treated with BB and CCB by pressures from 2.5 to 8.5 bar during three periods of time

Bamboo species	Sample	Time (min)	BB					CCB				
			Pressure (bar)									
			2.5	4.0	5.5	7.0	8.5	2.5	4.0	5.5	7.0	8.5
B. stenostachya	Bottom											
	MC2	60	2	3	4	4	4	1	3	4	4	4
		90	2	4	4	4	4	1	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
	MC1	60	1	4	4	4	4	2	4	4	4	4
		90	2	4	4	4	4	1	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
	Middle											
	MC2	60	1	3	4	4	4	1	4	4	4	4
		90	1	4	4	4	4	3	4	4	4	4
		120	2	4	4	4	4	3	4	4	4	4
	MC1	60	2	3	4	4	4	1	3	4	4	4
		90	2	4	4	4	4	3	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
D. asper	Bottom											
	MC2	60	2	3	4	4	4	2	3	4	4	4
		90	2	3	4	4	4	2	4	4	4	4
		120	2	4	4	4	4	3	4	4	4	4
	MC1	60	1	3	4	4	4	1	4	4	4	4
		90	1	4	4	4	4	1	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
	Middle											
	MC2	60	2	3	4	4	4	1	4	4	4	4
		90	1	3	4	4	4	3	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
	MC1	60	1	4	4	4	4	2	4	4	4	4
		90	1	4	4	4	4	2	4	4	4	4
		120	2	4	4	4	4	3	4	4	4	4
T. siamensis	Bottom											
	MC2	60	2	4	4	4	4	2	4	4	4	4
		90	2	4	4	4	4	2	4	4	4	4
		120	3	4	4	4	4	4	4	4	4	4
	MC1	60	2	4	4	4	4	2	4	4	4	4
		90	2	4	4	4	4	2	4	4	4	4
		120	3	4	4	4	4	3	4	4	4	4
	Middle											
	MC2	60	3	4	4	4	4	3	4	4	4	4
		90	2	4	4	4	4	3	4	4	4	4
		120	4	4	4	4	4	4	4	4	4	4
	MC1	60	3	4	4	4	4	3	4	4	4	4
		90	2	4	4	4	4	3	4	4	4	4
		120	4	4	4	4	4	4	4	4	4	4

MC1 : 15 – 20%; MC2:30 – 40%

Table 4a. Average retention (kg/m^3) of three bamboo species treated with BB according to 15 schedules

Treatment schedule		*B. stenostachya*				*D. asper*				*T. siamensis*			
Pressure	Time	Bottom		Middle		Bottom		Middle		Bottom		Middle	
(bar)	(min)	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1
2.5	60	3.1	3.4	3.6	4.0	2.7	3.1	3.0	3.4	3.6	3.7	3.9	4.5
		(0.9)	(0.6)	(0.7)	(1.3)	(1.2)	(0.6)	(0.9)	(0.7)	(1.1)	(0.9)	(0.9)	(0.7)
2.5	90	3.4	3.7	3.9	4.6	3.1	3.4	3.3	3.7	3.7	4.2	4.6	5.1
		(0.5)	(0.8)	(0.6)	(1.2)	(0.6)	(0.5)	(0.7)	(0.6)	(0.8)	(1.0)	(1.1)	(0.8)
2.5	120	3.6	4.2	4.3	4.7	3.3	3.7	3.8	4.0	3.2	3.7	4.5	5.4
		(0.7)	(0.5)	(0.8)	(1.2)	(0.6)	(1.1)	(0.9)	(0.7)	(1.3)	(0.8)	(0.7)	(0.9)
4	60	3.9	4.4	4.6	5.3	3.6	3.9	4.0	4.4	4.4	4.7	5.5	6.0
		(0.8)	(1.0)	(0.7)	(0.6)	(0.7)	(1.1)	(0.8)	(0.5)	(0.9)	(1.2)	(1.0)	(0.9)
4	90	4.4	4.8	4.8	5.7	4.0	4.4	4.3	4.6	4.7	5.2	6.0	6.9
		(0.9)	(0.8)	(0.5)	(1.1)	(0.8)	(0.9)	(0.5)	(0.6)	(1.0)	(1.2)	(0.8)	(0.9)
4	120	4.8	5.4	5.4	6.2	4.3	4.7	4.5	5.3	5.2	5.6	6.6	7.4
		(1.1)	(0.7)	(1.1)	(0.5)	(0.6)	(0.9)	(0.7)	(0.9)	(0.9)	(1.2)	(0.5)	(0.5)
5.5	60	5.1	5.7	5.8	6.5	4.7	5.0	5.3	5.8	5.6	6.2	7.1	7.9
		(0.5)	(1.3)	(0.7)	(0.7)	(0.9)	(0.6)	(0.8)	(0.5)	(1.4)	(0.9)	(0.7)	(0.7)
5.5	90	5.9	6.3	6.2	7.0	5.5	5.8	6.0	6.2	6.2	7.1	7.5	8.9
		(0.8)	(0.9)	(0.7)	(0.5)	(0.6)	(1.0)	(1.2)	(0.6)	(1.0)	(1.3)	(0.9)	(0.6)
5.5	120	6.7	7.1	7.4	8.4	5.8	6.7	6.4	7.0	7.2	7.8	9.1	9.6
		(0.6)	(1.3)	(1.0)	(1.1)	(1.2)	(0.7)	(1.5)	(0.7)	(1.5)	(1.2)	(0.8)	(1.0)
7	60	6.8	7.5	7.8	9.2	6.2	7.0	6.7	7.7	7.8	9.1	9.3	11.0
		(0.8)	(1.0)	(0.6)	(0.7)	(0.5)	(0.8)	(0.6)	(0.5)	(1.1)	(0.9)	(0.8)	(0.9)
7	90	7.7	8.4	8.9	10.2	6.6	7.8	7.5	8.5	9.2	10.4	10.7	12.1
		(0.7)	(1.4)	(0.8)	(0.9)	(1.1)	(0.6)	(0.5)	(0.8)	(1.0)	(1.1)	(0.6)	(0.7)
7	120	8.9	9.5	9.7	11.3	7.9	8.8	8.4	9.8	10.2	11.1	11.6	12.8
		(0.6)	(1.2)	(0.9)	(0.5)	(0.8)	(1.4)	(0.7)	(0.6)	(1.5)	(0.8)	(0.7)	(1.1)
8.5	60	9.4	10.1	10.3	11.7	8.1	9.4	9.2	10.7	11.7	12.0	13.0	13.5
		(0.9)	(1.1)	(0.8)	(1.5)	(0.7)	(0.9)	(0.8)	(1.0)	(1.6)	(1.0)	(1.3)	(0.8)
8.5	90	10.9	11.9	11.7	12.8	9.2	10.2	9.7	11.2	12.1	12.5	13.8	14.3
		(0.9)	(0.6)	(1.2)	(0.8)	(0.5)	(0.7)	(0.9)	(1.5)	(0.8)	(1.0)	(1.2)	(0.9)
8.5	120	11.4	12.7	12.5	13.8	10.0	11.2	10.8	11.9	12.7	13.2	14.4	15.5
		(1.1)	(0.7)	(1.0)	(0.9)	(1.4)	(0.8)	(1.1)	(0.9)	(1.5)	(0.9)	(1.0)	(0.7)

MC2 : 30 - 40%; MC1 : 15 - 20% ; Values in parentheses are standard deviation

Retention depending on the impregnation schedule

Generally, the treatment with BB resulted in a lower retention than with CCB, as also stated by Wahab *et al*. (2005). The preservative uptake increased significantly with the pressure from 2.5 - 8.5 bar. Regardless of culm portion and moisture content, the mean retention varied according to the pressure applied for *B. stenostachya* with BB from 3 - 14 kg/m^3 and with CCB from 3.5 - 16 kg/m^3. *D. asper* absorbed 2.5 - 12 kg/m^3 of BB and 3.5 – 14.5 kg/m^3 of CCB. The uptake of *T. siamensis* was from 3.5 - 15.5 kg/m^3 with BB and 4 - 17.5 kg/m^3 with CCB.

With the pressure of 8.5 bar, defects like end splits and node checks occurred in some samples of *D. asper*, whereas the other two species did not show such damage.

Table 4b. Average retention (kg/m^3) of three bamboo species treated with CCB according to 15 schedules

Treatment schedule		*B. stenostachya*				*D. asper*				*T. siamensis*			
Pressure	Time	Bottom		Middle		Bottom		Middle		Bottom		Middle	
(bar)	(min)	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1	MC2	MC1
2.5	60	3.5	4.1	3.7	4.1	3.4	3.9	3.7	4.2	3.9	4.4	5.1	5.5
		(0.6)	(0.8)	(1.1)	(0.7)	(0.8)	(1.2)	(0.9)	(0.7)	(1.3)	(0.9)	(0.5)	(0.8)
2.5	90	3.7	4.3	4.9	5.2	3.5	4.1	4.2	4.4	4.3	4.5	5.9	6.1
		(0.7)	(1.3)	(0.6)	(0.9)	(1.2)	(0.8)	(1.4)	(0.6)	(1.3)	(0.9)	(0.7)	(0.6)
2.5	120	4.1	4.7	5.1	5.5	3.7	4.0	4.3	4.9	5.1	5.9	6.1	6.5
		(0.9)	(0.5)	(1.4)	(0.8)	(0.6)	(1.2)	(0.7)	(0.5)	(1.3)	(1.0)	(0.9)	(0.6)
4	60	5.1	5.4	6.2	6.7	4.4	4.8	5.1	5.5	5.5	6.2	7.1	7.9
		(0.8)	(0.6)	(0.5)	(1.0)	(0.4)	(0.9)	(0.6)	(0.9)	(1.1)	(0.9)	(1.3)	(0.9)
4	90	5.9	6.1	6.5	7.1	4.9	5.4	5.6	6.1	6.2	6.6	7.5	8.5
		(0.7)	(1.1)	(1.2)	(0.6)	(0.9)	(0.7)	(1.2)	(0.6)	(1.4)	(1.0)	(0.8)	(1.0)
4	120	6.5	6.7	7.0	7.9	5.7	6.2	6.2	6.8	7.0	7.5	7.9	9.1
		(1.0)	(0.9)	(0.6)	(1.2)	(0.8)	(0.4)	(0.5)	(1.0)	(0.9)	(1.1)	(0.9)	(0.8)
5.5	60	6.8	7.3	7.2	8.7	6.0	6.9	6.6	7.3	7.9	8.6	8.8	10.5
		(0.5)	(0.9)	(0.7)	(1.2)	(1.0)	(0.7)	(0.9)	(0.6)	(1.2)	(1.6)	(0.5)	(0.7)
5.5	90	7.5	8.5	8.6	9.6	6.6	7.8	7.5	8.7	9.1	10.1	9.9	11.9
		(1.3)	(0.7)	(1.1)	(1.5)	(0.9)	(0.6)	(0.8)	(1.2)	(1.4)	(0.9)	(0.6)	(1.4)
5.5	120	8.5	9.0	9.8	10.7	7.7	8.0	8.4	9.1	10.3	11.1	11.2	12.9
		(0.6)	(1.0)	(1.0)	(0.5)	(1.0)	(0.4)	(0.7)	(0.6)	(0.9)	(1.5)	(1.3)	(0.8)
7	60	10.1	10.9	10.8	11.8	8.5	9.9	9.0	10.7	10.9	11.5	11.8	13.1
		(0.8)	(0.5)	(0.7)	(1.2)	(0.8)	(1.2)	(1.5)	(0.9)	(1.1)	(0.7)	(1.5)	(0.6)
7	90	10.9	11.9	12.0	13.0	9.5	11.0	10.2	11.6	11.5	12.9	12.8	14.5
		(0.9)	(1.1)	(0.8)	(0.9)	(1.2)	(0.9)	(0.6)	(1.0)	(1.0)	(1.3)	(0.9)	(1.4)
7	120	12.0	12.7	13.1	14.1	10.9	11.5	11.3	12.8	12.9	13.7	14.4	15.9
		(0.8)	(0.7)	(0.6)	(1.3)	(0.6)	(1.2)	(0.5)	(0.8)	(1.1)	(0.9)	(0.7)	(1.1)
8.5	60	12.2	13.0	13.7	14.7	11.3	12.2	11.9	13.2	13.5	14.1	15.4	16.3
		(1.4)	(0.6)	(0.9)	(1.0)	(1.3)	(1.1)	(0.7)	(0.9)	(1.6)	(0.8)	(0.5)	(0.9)
8.5	90	13.4	14.2	14.4	15.5	11.7	12.4	12.9	14.2	14.3	14.9	16.1	17.1
		(1.5)	(1.2)	(0.8)	(1.4)	(1.0)	(1.2)	(0.7)	(0.7)	(1.1)	(1.2)	(1.0)	(1.0)
8.5	120	13.8	14.6	14.9	15.9	13.1	14.0	13.9	14.4	14.9	15.5	16.4	17.5
		(0.6)	(1.0)	(0.7)	(1.0)	(1.4)	(0.9)	(1.1)	(0.8)	(1.5)	(0.9)	(1.1)	(0.8)

MC2 : 30 - 40%; MC1 : 15 - 20% ; Values in parentheses are standard deviation

Table 4c. Statistical analysis of variance for the effect of species, position, moisture content, preservative, pressure and time on retention

Source	DF	Mean Squares	F value
Species	2	122.12	10.02***
Position	1	96.72	7.70**
Moisture content	1	55.22	4.36*
Preservative	1	338.72	28.49**
Pressure	4	898.49	318.70***
Time	2	62.8	5.02**

Significant at: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

The period of pressure also affects the preservative uptake with increased retention. The relationship between pressure, time and retention was determined using regression analysis. Table 5 indicates a linear relationship with a high coefficient ($R^2 > 95\%$). This information could be applied in determining the treatment schedule for the species investigated relevant to the required retention.

Table 5. Regression equations for the retention of the three bamboo species with two preservatives (at 95% confidence level)

Species	Preservative	Position	Moisture content (%)	Linear regression equation	R^2
B. stenostachya	BB	Bottom	30 - 40	$y= - 2.25 + 1.18\ x_1 + 0.02\ x_2$	0.957
			15 - 20	$y= - 2.32 + 1.28\ x_1 + 0.02\ x_2$	0.953
		Middle	30 - 40	$y= - 2.01 + 1.26\ x_1 + 0.02\ x_2$	0.959
			15 - 20	$y= - 1.98 + 1.41\ x_1 + 0.03\ x_2$	0.967
	CCB	Bottom	30 - 40	$y= - 2.66 + 1.59\ x_1 + 0.02\ x_2$	0.975
			15 - 20	$y= - 2.34 + 1.66\ x_1 + 0.02\ x_2$	0.982
		Middle	30 - 40	$y= - 2.44 + 1.66\ x_1 + 0.03\ x_2$	0.983
			15 - 20	$y= - 2.15 + 1.77\ x_1 + 0.03\ x_2$	0.993
D.asper	BB	Bottom	30 - 40	$y= - 1.65 + 1.01\ x_1 + 0.02\ x_2$	0.966
			15 - 20	$y= - 1.97 + 1.15\ x_1 + 0.02\ x_2$	0.965
		Middle	30 - 40	$y= - 1.52 + 1.09\ x_1 + 0.02\ x_2$	0.970
			15 - 20	$y= - 1.86 + 1.27\ x_1 + 0.02\ x_2$	0.967
	CCB	Bottom	30 - 40	$y= - 2.79 + 1.44\ x_1 + 0.02\ x_2$	0.975
			15 - 20	$y= - 2.12 + 1.54\ x_1 + 0.02\ x_2$	0.977
		Middle	30 - 40	$y= - 2.43 + 1.48\ x_1 + 0.02\ x_2$	0.980
			15 - 20	$y= - 2.16 + 1.63\ x_1 + 0.02\ x_2$	0.983
T. siamensis	BB	Bottom	30 - 40	$y= - 1.66 + 1.00\ x_1 + 0.02\ x_2$	0.966
			15 - 20	$y= - 2.17 + 1.49\ x_1 + 0.02\ x_2$	0.970
		Middle	30 - 40	$y= - 2.25 + 1.55\ x_1 + 0.02\ x_2$	0.974
			15 - 20	$y= - 1.77 + 1.60\ x_1 + 0.02\ x_2$	0.987
	CCB	Bottom	30 - 40	$y= - 2.61 + 1.67\ x_1 + 0.03\ x_2$	0.993
			15 - 20	$y= - 2.27 + 1.71\ x_1 + 0.03\ x_2$	0.989
		Middle	30 - 40	$y= - 1.46 + 1.73\ x_1 + 0.02\ x_2$	0.983
			15 - 20	$y= - 1.24 + 1.86\ x_1 + 0.03\ x_2$	0.992

whereby y is retention (kg/m^3); x_1 is pressure intensity (bar) and x_2 is pressure time (minute) with $2.5 < x_1 < 8.5$ and $60 < x_2 < 120$

Gradient of retention along and across the culm part

The gradient of the retention within the culm part was investigated at the two ends, in the middle of the sample and on a radial section. Five replicates from each treatment schedule were tested by chemical analysis (Table 6 a, b, c).

There was considerable variation of the retention from the ends to the middle of the sample since absorption at the ends was higher due to the open vessels. Across the culm wall, the highest retention occurred at the inner layer, followed by the outer layer and the center. This result is confirmed by Kumar *et al.* (1992).

Table 6a. Variation of retention (kg/m^3) for *B. stenostachya* depending on the position of sampling

Preservative	Schedule		Sample condition	along culm E1	E0	E2	radial direction Outer	Center	Inner
BB	5.5 bar for 60 min	B	MC2	6.8 a	4.9 b	6.5 a	5.5 ab	5.0 a	6.0 b
			MC1	7.2 a	5.5 b	6.8 a	5.9 ab	5.6 a	6.8 b
		M	MC2	7.7 a	5.8 b	7.2 a	6.6 ab	5.9 a	7.0 b
			MC1	9.4 a	6.9 b	8.6 a	7.5 ab	7.3 a	8.2 b
	5.5 bar for 90 min	B	MC2	7.2 a	5.6 b	6.7 a	6.4 ab	6.2 a	7.1 b
			MC1	7.8 a	5.9 b	7.5 a	6.6 a	6.1 a	7.6 b
		M	MC2	8.2 a	6.0 b	7.5 a	6.8 ab	6.2 a	7.8 b
			MC1	9.1 a	7.2 b	8.9 a	7.9 ab	7.4 a	8.9 b
	5.5 bar for 120 min	B	MC2	9.1 a	6.4 b	8.2 a	7.1 a	6.6 a	7.4 a
			MC1	8.5 a	6.7 b	8.1 a	7.6 a	7.0 a	8.9 b
		M	MC2	9.6 a	7.4 b	9.0 a	8.4 ab	7.6 a	8.7 b
			MC1	10.9 a	8.0 b	10.1 a	8.8 ab	8.3 a	9.5 b
CCB	7 bar for 60 min	B	MC2	12.8 a	10.5 b	12.0 a	11.7 ab	10.8 a	12.3 b
			MC1	12.9 a	10.7 b	12.3 a	11.8 ab	11.2 a	12.9 b
		M	MC2	13.4 a	10.9 b	12.9 a	12.8 ab	11.7 a	13.3 b
			MC1	14.4 a	11.2 b	13.8 a	12.0 ab	11.4 a	13.2 b
	7 bar for 90 min	B	MC2	14.3 a	10.3 b	13.1 a	11.3 ab	10.7 a	12.5 b
			MC1	14.9 a	11.6 b	13.7 c	13.0 a	12.5 a	14.1 b
		M	MC2	14.5 a	11.7 b	13.6 a	12.6 ab	11.4 a	13.5 b
			MC1	15.7 a	12.6 b	14.6 a	13.8 a	12.9 a	15.1 b
	7 bar for 120 min	B	MC2	15.3 a	11.2 b	13.9 c	12.7 a	11.8 a	13.9 b
			MC1	16.0 a	12.5 b	14.5 c	13.2 a	12.8 a	14.6 b
		M	MC2	16.4 a	12.4 b	14.8 c	13.0 a	12.7 a	13.7 a
			MC1	17.3 a	13.8 b	15.3 c	15.5 b	14.1 a	16.0 b

B: Bottom; M: Middle; MC2 : 30 - 40%; MC1 : 15 - 20%; E1 & E2 : two ends ; E0: middle section
Means having different letters in the same row are significantly different ($P < 0.05$)

The higher retention at the ends as well as in the outer and inner layers of the culm part will be beneficial in service since these parts come first in contact with fungi and insects.

CONCLUSIONS

The preservative absorption of the three bamboos investigated had a distinct dependence on the species, the culm portion, the preservative and especially on the pressure and time applied. Significant linear relationships between them were indicated to provide information, which could be applied in determining the treatment schedule for these species.

From a practical point for reducing seasoning time, a moisture range of 30 - 40% could be used instead of 15 - 20% moisture as sometimes applied.

Considering these results with the recommendations of 4 kg/m^3 BB for indoor furniture and 10 kg/m^3 CCB for outdoor exposure (Liese and Kumar, 2003), the following treatment schedule is recommended:

Table 6b. Variation of retention (kg/m^3) for *D. asper* depending on the position of sampling

Preservative	Schedule	Sample condition		along culm E1	E0	E2	radial direction Outer	Center	Inner
BB	5.5 bar for 60 min	B	MC2	6.1 a	4.6 b	5.9 a	4.9 ab	4.1 a	5.3 b
			MC1	6.3 a	4.8 b	5.8 a	5.8 ab	5.0 a	6.0 b
		M	MC2	6.9 a	5.0 b	6.4 a	5.9 ab	5.2 a	6.1 b
			MC1	7.5 a	5.7 b	7.1 a	6.2 ab	5.7 a	7.0 b
	5.5 bar for 90 min	B	MC2	6.9 a	5.4 b	6.8 a	5.8 ab	5.4 a	6.5 b
			MC1	7.1 a	5.6 b	6.9 a	6.0 ab	5.8 a	7.3 b
		M	MC2	7.3 a	5.8 b	6.7 ab	6.4ab	6.2 a	7.2 b
			MC1	8.3 a	6.0 b	8.0 a	6.9 ab	6.5 a	7.5 b
	5.5 bar for 120 min	B	MC2	7.3 a	5.7 b	7.0 a	6.1 a	6.0 a	7.4 b
			MC1	8.1 a	6.4 b	7.6 a	6.7 ab	6.5 a	7.7 b
		M	MC2	7.9 a	6.2 b	7.6 a	6.9 ab	5.9 a	7.1 b
			MC1	9.0 a	7.2 b	8.5 a	7.7 ab	7.4 a	8.3 b
CCB	7 bar for 60 min	B	MC2	9.9 a	8.2 b	9.7 a	8.8 ab	8.2 a	9.5 b
			MC1	12.4 a	9.3 b	11.7 a	10.8 a	9.6 b	11.6 a
		M	MC2	10.9 a	8.9 b	10.4 a	9.3 ab	9.2 a	10.4 b
			MC1	12.8 a	10.4 b	11.9 a	11.7 a	11.4 a	12.0 a
	7 bar for 90 min	B	MC2	12.2 a	8.8 b	11.3 a	9.7 ab	8.9 a	9.9 b
			MC1	13.5 a	10.7 b	13.0 a	11.6 a	11.2 a	11.9 a
		M	MC2	12.3 a	10.0 b	11.5 a	10.8 a	10.3 a	11.2 a
			MC1	13.6 a	11.2 b	13.0 a	12.1 ab	11.3 a	12.3 b
	7 bar for 120 min	B	MC2	13.9 a	11.1 b	13.1 a	12.2 a	11.4 a	13.5 b
			MC1	14.2 a	11.4 b	12.8 c	12.6 ab	12.0 a	13.8 b
		M	MC2	13.3 a	11.5 b	12.8 a	12.9 a	12.0 a	13.3 a
			MC1	15.0 a	12.6 b	14.7 a	13.4 ab	13.0 a	14.5 b

B: Bottom; M: Middle; MC2 : 30 - 40%; MC1 : 15 - 20%; E1 & E2 : two ends ; E0: middle section
Means having different letters in the same row are significantly different ($P < 0.05$)

For indoor use with BB, *T. siamensis* needs a pressure of 4 bar for 60 minutes, whereas for *B. stenostachya* and *D. asper* 5.5 bar for 60 minutes is required.

For outdoor application with CCB, *T. siamensis* demands a pressure of 5.5 bar for 120 minutes, but *B. stenostachya* and *D. asper* need 7 bar for 60 and 120 minutes, respectively.

ACKNOWLEDGEMENTS

We would like to thank the Duy Quy Company of Mechanical Engineering, Ho Chi Minh-City and the Bamboo Nature Company, Binh Duong Province, Vietnam, for providing materials and facilities in support for the project. Thanks are expressed to the assistance of Mr. Mai Van Cham and Ms. Ho Thuy Dung, Nong Lam University of HCM and of the staff of the Bamboo Nature Company for the work in Vietnam. We also acknowledge the help of Ms. Karin Brandt, Mr. Sergej Kaschuro, Dr. Eckhard Melcher and Mr. Thomas Schwarz, Thünen Institute for Wood Technology and Biology, Hamburg, and the comments by Prof. Dieter Eckstein and Prof. Olaf Schmidt, Department of Wood Biology, University Hamburg.

Table 6c. Variation of retention (kg/m^3) for *T. siamensis* depending on the position of sampling

Preservative	Schedule		Sample condition	along culm E1	E0	E2	radial direction Outer	Center	Inner
BB	4 bar for 60 min	B	MC2	6.4 a	4.2 b	5.8 a	5.7 b	4.8 ab	4.5 a
			MC1	6.3 a	4.6 b	5.9 a	6.1 b	5.9 ab	4.9 a
		M	MC2	7.2 a	5.7 b	6.8 a	6.6 ab	6.0 a	7.2 b
			MC1	8.6 a	6.3 b	8.2 a	7.4 ab	6.6 a	7.7 b
	4 bar for 90 min	B	MC2	5.9 a	4.5 b	5.5 a	5.9 b	5.1 ab	4.8 a
			MC1	7.5 a	5.3 b	6.87 a	6.9 b	6.1 ab	5.7 a
		M	MC2	8.5 a	6.0 b	7.7 a	6.7 ab	6.2 a	7.4 b
			MC1	8.8 a	7.1 b	8.2 a	8.3 ab	7.5 a	8.6 b
	4 bar for 120 min	B	MC2	7.2 a	4.9 b	7.0 a	6.2 b	5.7 ab	5.2 a
			MC1	8.6 a	5.7 b	7.8 a	7.1 b	6.5 ab	6.3 a
		M	MC2	8.8 a	6.4 b	8.4 a	7.1 ab	6.5 a	7.8 b
			MC1	10.4 a	7.5 b	10.2 a	8.6 a	7.8 a	8.8 a
CCB	5.5 bar for 60 min	B	MC2	10.5 a	7.8 b	9.75 a	9.8 b	8.7 a	8.2 a
			MC1	10.2 a	8.3 b	9.7 a	10.4 b	9.4 ab	8.6 a
		M	MC2	11.3 a	8.5 b	10.4 a	9.2 a	8.9 a	10.0 a
			MC1	13.4 a	10.6 b	12.8 a	11.3 a	10.8 ab	12.4 b
	5.5 bar for 90 min	B	MC2	12.1 a	8.4 b	11.7 a	11.0 b	9.5 a	9.1 a
			MC1	12.4 a	9.7 b	11.4 a	12.5 b	11.8 b	10.2 a
		M	MC2	12.7 a	9.8 b	12.1 a	10.9 ab	10.0 a	11.4 b
			MC1	15.5 a	11.6 b	14.4 a	13.4 a	12.0 b	14.1 a
	5.5 bar for 120 min	B	MC2	14.5 a	10.2 b	14.2 a	13.3 b	12.7 b	10.5 a
			MC1	15.3 a	11.7 b	14.0 c	14.7 b	13.8 ab	12.9 a
		M	MC2	14.5 a	10.3 b	13.8 a	11.5 ab	10.6 a	11.8 b
			MC1	17.5 a	12.6 b	16.4 a	14.1 ab	13.0 a	14.4 b

B: Bottom; M: Middle; MC2 : 30 - 40%; MC1 : 15 - 20%; E1 & E2 : two ends ; E0: middle section
Means having different letters in the same row are significantly different ($P < 0.05$)

REFERENCES

Grosser, D. and Liese, W. 1971. On the anatomy of Asian bamboos, with special reference to their vascular bundles. *Wood Sci. and Technol.* 5: 290-312.

Hoang, T. T. H. and Tang, T. K. H. 2007. Structural features and physical properties of some important South Vietnam bamboo species. *Journal of Agriculture-Forestry Sciences and Technology of Nong Lam University of HCM* 3: 15-22.

Kumar, S. and Dobrial, P.B. 1992. Treatability and flow path studies in bamboo: Part I. *Dendrocalamus stratus* Nees. *Wood and Fiber Sci. 42(2)*: 113-117.

Kumar, S., Shukla, K.S., Dev, I. and Dobriyal, P.B.1994. Bamboo Preservation Techniques: A Review. INBAR and ICFRE: 55 p.

Liese, W. 1998. The anatomy of bamboo culms. *INBAR Technical Report* 18**,** Beijing: 204 p.

Liese, W. and Kumar, S. 2001. Bamboo preservation compendium. *INBAR Technical Report* 22 Beijing: 231 p.

Nguyen, T. B.N. 2005. Investigation on preservative treatment of bamboos using for construction and furniture. PhD Dissertation. Publ. in Forest Science Institute of Vietnam: 155 p.

Tang, T. K. H. 2009. Bamboo preservation in Vietnam. *Documents of the 40th Conference of International Research Group on Wood Protection*, 24–28 May 2009, Beijing**:** 1-11.

Wahab, R., Sudin, M., Mokhtar, J. and Mohd A. A. 2005. Penetration class and net dry salt retention of ammoniacal copper quartenary, borax boric acid and copper chrome arsenic in 2 and 4 year-old bamboo *Gigantochloa scortechinii*. *J. Biol. Sci.* 5(4): 511-518.

Bamboo Science and Culture:
The Journal of the American Bamboo Society 25(1): 27-35

Investigation on optimisation of kiln drying for the bamboo species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*

Thi Kim Hong Tang[1,3], Johannes Welling[2], Thuy Dung Ho[3], Walter Liese[1]

[1]Center for Wood Science, University Hamburg
Leuschnerstr. 91, D 21031 Hamburg, Germany

[2]vTI Institute of Wood Technology and Biology
Leuschnerstr. 91, D 21031 Hamburg, Germany

[3]Faculty of Forestry, Nong Lam University of HCM, Linh Trung Ward, Thu Duc–District, Ho Chi Minh City, Vietnam

ABSTRACT

Results on kiln drying of the bamboo species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis* are presented. Samples of culm parts at basic and middle sections of the species were dried in a pilot kiln using three different schedules with grades of low, middle and high drying rate. The moisture loss, drying time and drying defects were determined.

Culms of the solid species *Thyrsostachys siamensis* are easier to dry than the cavity species *Bambusa stenostachya, Dendrocalamus asper*. For fresh culms of *Thyrsostachys siamensis* with initial moisture content of over 100 % the drying time to reach a final moisture content of 10% by applying a severe drying schedule was 7 days for the middle part and 9 days for the basic part. *Dendrocalamus aspe*r is the most difficult species to dry and severely susceptible to checks and splits, so that it needed a mild drying schedule and drying time of 13 days for middle and 16 days for basic part. *Bambusa stenostachya* dries moderately using a relative milder drying schedule with 10 days for the middle and 12 days for the basic part.

Keywords: Bamboo drying, *T. siamensis, B. stenostachya, D. asper*

INTRODUCTION

Bamboo is one of the important vegetative ligno–cellulose resources besides plantation wood. In many tropical countries it is a major raw material for the forest product industry. In recent years, bamboo has become a main material for the industrial manufacturing of round and laminated furniture, parquet and for the worldwide export of culms.

Drying is a key step in processing bamboo products and solving the drying problems will add further value to bamboo resource. Well-dried bamboo culms have the desired appearance, finish and structural properties for the successful export into high value markets. Dried culms are more easily and efficiently processed in steps such as cutting, machining and finishing during production of high quality products. Proper drying also reduces weight, preserves colour, improves the strength of the bamboo, inhibits infestations and minimizes shrinkage in service.

The traditional method of drying bamboo is simple air drying. It has been commonly used for a long time in rural areas and in bamboo factories with small capacities. With proper stacking for air circulation, culms can be dried with no further energy than contained in the ambient air. However, there are some disadvantages. One is the long drying time, which can range from several weeks to several months to obtain the required moisture content for end use. Furthermore, bamboo can be easily infected by fungi, especially moulds during drying. Air drying depends largely on climatic conditions and is undertaken under uncontrollable conditions.

Kiln drying provides means for overcoming these limitations. The significant advantages of kiln drying include higher throughput and better control of the required moisture content. Kiln drying enables bamboo to be dried to any moisture content regardless of weather conditions. For large–scale drying operations, kiln drying is more efficient than air drying and could ensure high level bamboo quality.

In Vietnam the demand for the export of large quantities of quality products has recently increased. Bamboo manufacturers recognized the disadvantages of air drying and have introduced dry kiln techniques. However, considerable problems with drying still exist because the development of bamboo kiln drying has rarely been supported by adequate research efforts.

To contribute to the development of bamboo kiln drying for the benefit of bamboo producers in Vietnam, the project ”Investigation on kiln drying of some commercial bamboo species of Vietnam” was initiated. It is supported by the Duy Quy Company of Mechanical Engineering, Ho Chi Minh City and the Bamboo Nature Company, Binh Duong Province, Vietnam. For this project, *Bambusa stenostachya* (Tre Gai), *Dendrocalamus asper* (Manh Tong) and *Thyrsostachys siamensis* (Tam Vong) were investigated, which are the most important bamboo species in South Vietnam for production of furniture and export. The goal is to develop suitable kiln dry schedules for culm parts of these species for furniture making.

MATERIALS AND METHODS

The experiments were carried out at the factory of the Bamboo Nature Company, Binh Duong province, South Vietnam during the rainy seasons from May to November in 2008, 2009 and 2010.

Bamboo samples

Mature 3 year old bamboo culms from *Bambusa stenostachya* Hackel (*Bambusa stenostachya* is a synonym of *Bambusa blumeana* J.H. Schultes. Flora of China 2006 Volume 22 Poaceae), *Dendrocalamus asper* (J.H. Schultes) Backer ex K. Heyne and *Thyrsostachys siamensis* Gamble were harvested from a bamboo plantation of the Bamboo Nature Company. Culms were cut about 25 centimetres from ground level and the basic, middle and top parts were marked. The material was transported the same day to the factory for further experiments.

Samples with a length of 140 cm were prepared from the basic and middle culm sections. The epidermis was removed by machine sanding as common for processing. Culm diameter and wall thickness were measured (see Table 1).

Lay out of the pilot dry–kiln

Dry–kiln

The experiments were performed in a pilot dry–kiln of 1.7m length, 1.5 m high and 1.2 m width. Its heating system was capable of generating temperatures up to 90°C by electrical heating coils located vertically near the kiln roof. The relative humidity was adjusted by hot water spraying and venting. The air circulation system consisted of two fans with 34 cm diameters. The air velocity was maintained at a constant speed of 3.5 m/s reflecting current industrial standards. The kiln was operated by means of a PLC-controller connected to a PC work station, ensuring control and monitoring of the drying protocol, temperature and relative humidity in the chamber in real time.

Kiln drying

Bamboo samples were dried in the dry–kiln. For the drying of *Thyrsostachys siamensis* 154 samples were stacked in 11 rows with 1 cm

Table 1. The dimensions of the samples tested

Species	Length (in mm)		Average diameter (in mm)		Average wall thickness (in mm)	
	Basic	Middle	Basic	Middle	Basic	Middle
T. siamensis	1400	1400	45	38	solid	11
B. stenostachya	1400	1400	80	72	15	10
D. asper	1400	1400	88	74	16	11

Photo 1. Stacking basic parts of *T. siamensis* and middle parts of *D. asper*

distance. For *Bambusa stenostachya* and *Dendrocalamus asper*, 64 samples were stacked in 8 rows with 1.5 cm distance (see Photo 1). Five controls of the sample lot were used to estimate the average moisture content and moisture loss.

During the drying process, the conditions in the kiln were adapted to predefined set point values in the schedule according to the mois ture content of the samples at various times during the run. The controls were weighed daily to compute the moisture content.

Drying schedules

The moisture content schedules applied had four grades of drying intensity: mild, medium and severe and very severe. The design of the schedules was based on the studies on bamboo drying by Laxamana (1985), Yosias (2002), Montoya Argango (2006) and Pham (2006). The drying schedules of tropical wood species published by Boone (1988) were also considered. The applied schedules are presented in Table 2.

For each of the bamboo species, three different schedules were tested. Schedule no.1 with mild drying intensity was applied to the cavity species *Bambusa stenostachya* and *Dendrocalamus asper.* Schedule no. 2 with medium drying and schedule no. 3 with severe drying intensity were also applied to these cavity species and also to the solid species *Thyrsostachys siamensis.* Schedule no. 4 with very severe drying conditions was tested only on *Thyrsostachys siamensis.*

Moisture content

The initial moisture content of the control sample was determined from the moisture sections cut from both ends of the control sample (see Fig. 1). The average moisture content of these two sections and the weight of the control sample at the time of cutting were used to calculate the oven-dry weight of the

Table 2: The conditions (set–point values) of the four drying schedules

Step	Moisture content (%)	No.1		No.2		No.3		No.4	
		T(°C)	RH (%)	T(°C)	RH (%)	T(°C)	RH (%)	T(°C)	RH (%)
1	Over 90	45	80	50	80	55	80	65	80
2	90 – 70	45	70	50	70	55	75	65	60
3	70 – 50	50	60	60	60	60	65	70	45
4	50 – 40	50	50	60	50	65	50	70	35
5	40 – 30	50	40	60	30	65	35	70	30
6	30 – 20	55	40	65	30	70	25	75	25
7	20 –10	55	30	65	20	70	20	75	15
Conditioning with 50°C T and 70% RH									

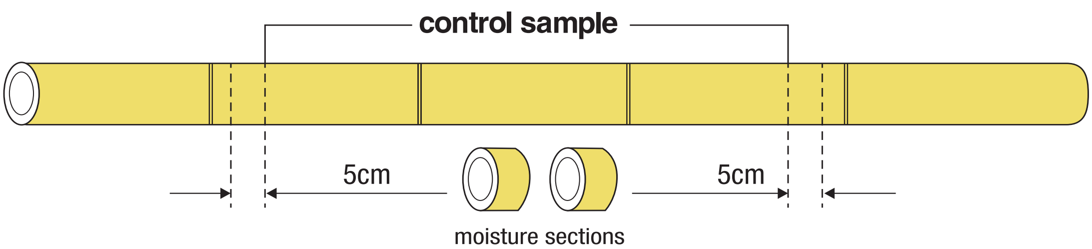

Fig.1: Method of cutting control sample and moisture content sections for initial MC

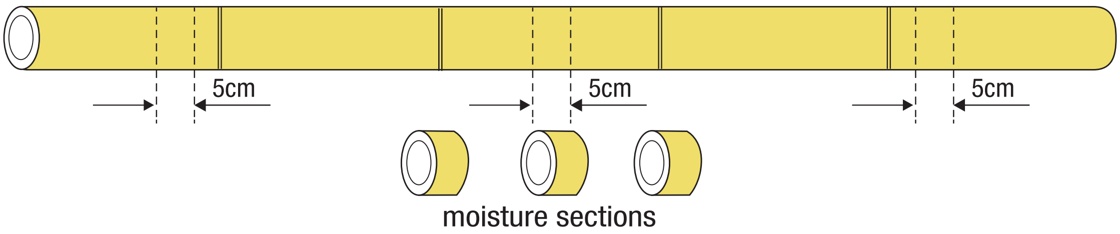

Fig.2: Method of cutting moisture content sections for final MC

control sample. The oven–dry weight and the subsequent weights of the sample obtained at intervals during drying, called current weights, were used to calculate the moisture content at those times. The moisture content (MC) of the moisture sections was determined by oven drying and calculated as

$$MC\ (\%) = 100(W_{or} - W_o)/\ W_o$$

with W_{or} as original weight of samples and W_o as oven dry weight. The ovendry weight of control sample (W_{oc}) was computed by using the following formula:

$$W_{oc} = (\text{original weight of control} / 100 + \text{average moisture content of two sections}) \times 100$$

For determination of the average initial moisture content, sections of 5 cm were cut from both ends of the samples. Five controls and five further samples were used.

To evaluate the moisture gradient and the final moisture content, sections of 5 cm were taken from both ends and from the middle of 13 samples (see Fig. 2). The drying rate was determined by the relationship between moisture decreases with drying time.

Drying defects

All culms of the drying experiment were visually inspected for defects like collapse, cracking, and splitting that had occurred during drying. Drying defects were expressed as percentage of all samples in each kiln run.

RESULTS AND DISCUSSION

All the results for the experiments with three bamboo species are summarized on Table 3.

Table 3. Summary of the results for the experiments with three bamboo species

Schedule	Result	*T. siamensis*		*B. stenostachya*		*D. asper*	
		B	M	B	M	B	M
No. 1	IMC (in %)	–	–	103	92	102	89
	FMC (in %)	–	–	10.4	10.1	9.3	8.2
	Defect (in %)	–	–	3.7	1.9	4.9	3.5
	Time (in hours)	–	–	350	326	370	302
No. 2	IMC	120	110	102	99	105	93
	FMC	8.5	10.1	9.6	9.5	9.2	10.4
	Defect	2.5	1.6	5.1	2.9	17.8	12.5
	Time	292	222	272	255	303	259
No. 3	IMC	119	106	105	96	108	92
	FMC	9.7	10.3	9.6	8.3	10.2	9.2
	Defect	4.8	3.9	15.7	18.9	28.9	19.5
	Time	245	195	255	208	282	236
No. 4	IMC	120	108	–	–	–	–
	FMC	8.8	10.2	–	–	–	–
	Defect	5.5	4.2	–	–	–	–
	Time	219	176	–	–	–	–

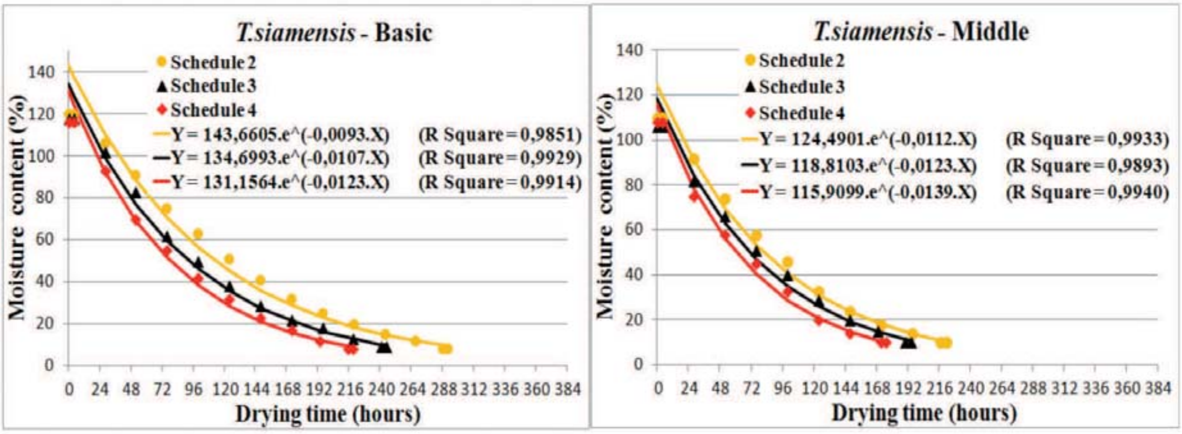

Fig.3. Relationship between drying time and moisture loss of *T. siamensis*

Drying rate and moisture loss

There is a notable difference in drying rate between the solid bamboo species *Thyrsostachys siamensis* and the cavity species *Bambusa stenostachya* and *Dendrocalamus asper*. The former showed a higher drying rate, whereas the other two dried more slowly.

This can be partly explained by the differences in specific gravity. In general, the heavier the wood is, the slower the drying rate and the greater the likelihood of defects will be (Simpson, 1992). The study on the physical and mechanical properties of the above mentioned bamboo species by Hoang et al. (2007) showed that the oven-dried density of *Thyrsostachys siamensis* was 0.41g/cm^3 for the basic and 0.46 g/cm^3 for middle part, whereas the species *Bambusa stenostachya* had oven-dried density values of 0.65 g/cm^3 and 0.72 g/cm^3 and *Dendrocalamus asper* of 0.71 g/cm^3 and 0.78 g/cm^3 respectively.

A difference in drying rate was also measured for the culm section. The middle section showed a higher drying rate than the basic part. This result could be explained by the physical and structural variation of a culm. Though the specific gravity of the middle is slightly higher than the basic part, wall thickness and the diameter of the basic part of the culm are greater than the middle one. Moreover, the middle section contains more vascular bundles than the basic (Liese 1998).

The loss of moisture occurred at a regular rate during all four drying schedules and is presented in Fig. 3, 4 and 5.

Final moisture content

The average final moisture content of the three species is reported in Table 4.

In the first drying run of schedule no.1 for *Bambusa stenostachya*, the basic samples showed a great variation of 3 to 16% of moisture content

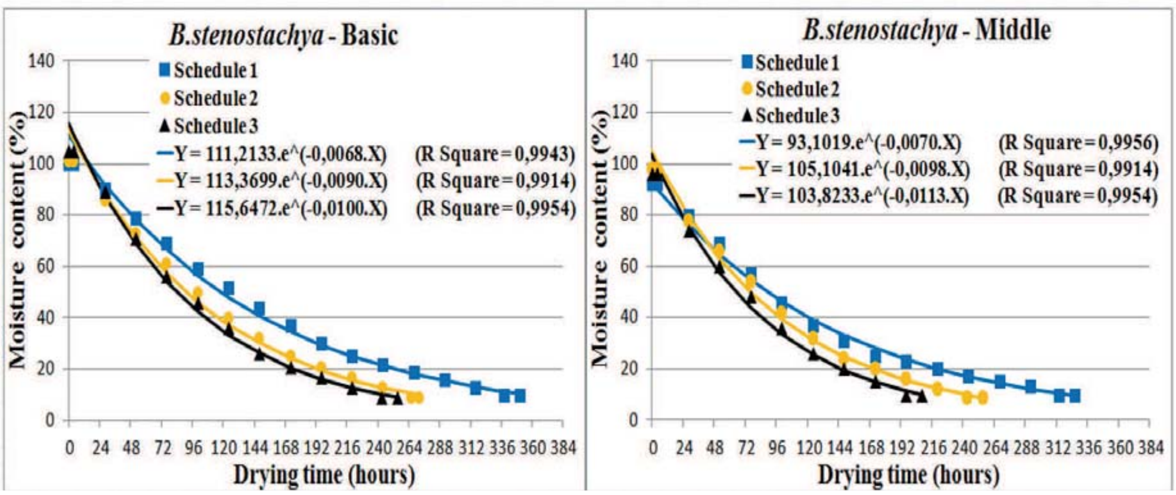

Fig. 4. Relationship between drying time and moisture loss of *B. stenostachya*

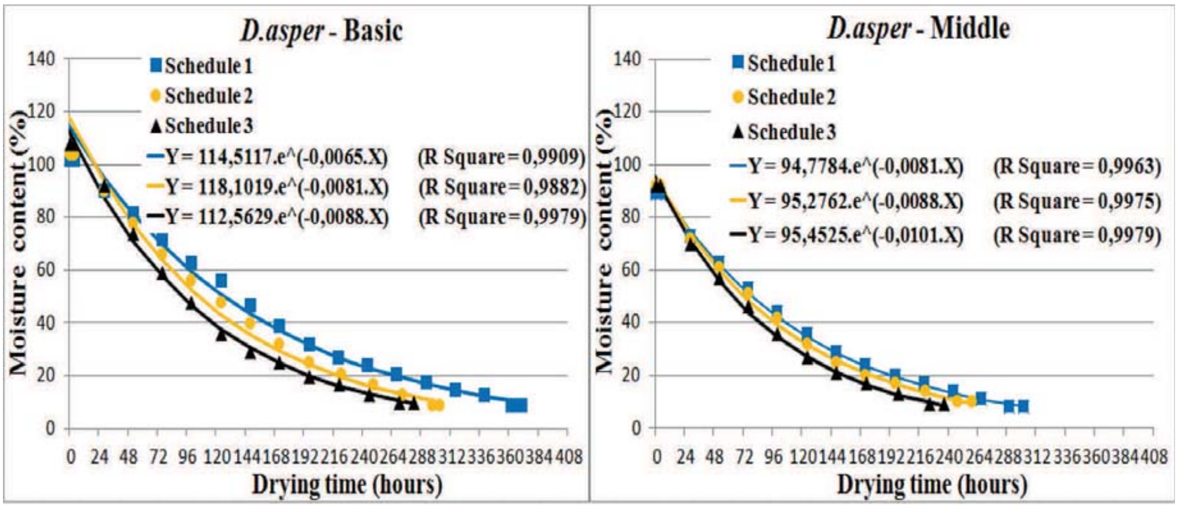

Fig. 5. Relationship between drying time and moisture loss of *D. asper*

among 13 tested samples. Variations in final moisture content can affect the machining and use of bamboo. To reduce the variation, the conditioning period was increased from 4 to 12 hours during the next drying runs of *Bambusa stenostachya* and *Dendrocalamus asper*. The conditioning of *Thyrsostachys siamensis* was kept short with 4 hours.

The average moisture content of the basic and middle parts after drying showed no pronounced differences. The final moisture content of the three species ranged from 6 to 12% for the basic and 7 to 11% for the middle with standard deviations of 1.2 to 1.4 for basic and 1.0 to 1.3 for middle parts.

Drying time

The time affected by the drying intensities from mild to severe is presented in Fig. 3, 4 and 5.

When using the milder schedule no. 1 with a final temperature of 55°C and RH of 30% on the species *Bambusa stenostachya,* the drying time for the basic sections was 350 hours for reducing the initial MC from higher than 100% to 9%. The middle parts dried in 326 hours with a reduction of MC from 98% to 9%.

By applying the medium schedule no. 2 with a temperature of 65°C and 20% RH, the time was reduced to 272 hours for the basic and 255 hours for the middle sections. The severe drying schedule no. 3 with a final temperature of 70°C and 20% RH procured drying time of 255 hours for the basic and 208 hours for middle sections. However, severe defects such as splits end and node checks developed in the both parts.

For *Dendrocalamus asper,* the severe drying schedule no. 3 had the shortest drying time of 282 hours for basic and 236 hours for the middle, but serious defects as splits developed. When applying the slightly milder schedule no. 2, the time increased to 303 hours for basic and 259 hours for middle sections, both with notable defects. The milder schedule no. 1 reduced defects, and the drying time was 370 hours for basic and 302 hours for the middle sections.

Schedule no. 3 and the very severe schedule no. 4 with higher temperature of 75°C and lower RH of 15% can be applied to reduce drying times for the solid species *Thyrsostachys siamensis.* For schedule no. 3, the time was 245 hours for basic and 195 hours for middle sections. The shortest time was achieved with schedule no. 4 with 219 hours for basic and 176 hours for middle sections.

In comparison to the kiln drying results by Laxamana (1985) for the species *Bambusa vulgaris, Dendrocalamus merillianus, Phyllostachys nigra* and *Schizostacbyum diffusum* and the studies on *Guadua angustifolia* by Montoya Arango (2006), the drying time was generally shorter than in these investigated species. Drying time for *Dendrocalamus merillianus* was 128 hours and for *Guadua angustifolia* 118 hours. The shortest time for *Thyrsostachys siamensis* was 176 hours, *Bambusa stenostachya* 208 hours and *Dendrocalamus asper* 236 hours.

Table 4: The average initial moisture content with samples n= 20 and the final moisture content with n = 39 of the four experiments

Schedule	Species		*T. siamensis*		*B. stenostachya*		*D. asper*	
	Moisture content		Basic	Middle	Basic	Middle	Basic	Middle
No. 1	Mean (in %)	initial	–	–	103	92	102	89
		final	–	–	10.4	10.1	9.3	8.2
	SD (in %)	initial	–	–	6.8	5	7.5	5.6
		final	–	–	1.4	1.2	1.3	1.1
	VC (in %)	final	–	–	13.8	12.1	14.4	13.6
	min	final	–	–	7.5	6.9	8.3	6.3
	max	final	–	–	12.1	12	12.4	12
No. 2	Mean (in %)	initial	120	110	102	99	105	93
		final	8.5	10.1	9.6	9.5	9.2	10.4
	SD (in %)	initial	8.8	7.2	6.1	5.9	6.9	4.8
		final	1.3	1.1	1.3	1.1	1.3	1
	VC (in %)	final	15.7	11.2	13.9	11.7	13.7	9.8
	min	final	6	6.9	6.9	5.9	6	5.9
	max	final	12.4	11.2	11.9	12.2	12.2	12
No. 3	Mean (in %)	initial	119	106	105	96	108	92
		final	9.7	10.3	9.6	8.3	10.2	9.2
	SD (in %)	initial	8.1	7.2	6.4	4.8	7.1	5.9
		final	1.2	1.3	1.4	1.1	1.4	1.1
	VC (in %)	final	12.8	12.5	14.9	13.1	14.1	11.5
	min	final	6.1	6.8	6	5.9	6.2	5.9
	max	final	12.4	11.6	11.9	12.4	11.8	12
No. 4	Mean (in %)	initial	120	108	–	–	–	–
		final	8.8	10.2	–	–	–	–
	SD (in %)	initial	8.2	7.1	–	–	–	–
		final	1.4	1.2	–	–	–	–
	VC (in %)	final	15.7	11.2	–	–	–	–
	min	final	6	7.3	–	–	–	–
	max	final	12.4	11.1	–	–	–	–

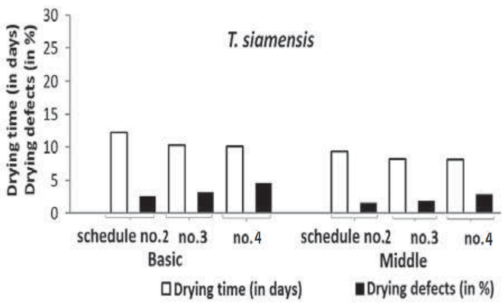

Fig. 6. Drying time and percentage of defects for *T. siamensis*

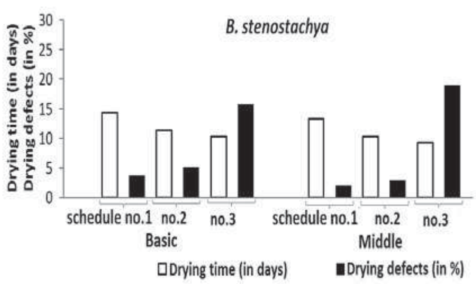

Fig. 7. Drying time and percentage of defects for *B. stenostachya*

The difference between the species is partly explained by their physical properties. *Bambusa stenostachya* has a specific gravity of 0.71 and a wall thickness of 20 mm which is less in comparison to *Dendrocalamus asper* (0.78 and 22mm, resp.) and more to *Dendrocalamus merillianus* (0.6 and 10 mm, resp.). *Guadua angustifolia* has a specific gravity of 0.6 and a wall thickness of 23 mm. The solid species *Thyrsostachys siamensis* has a low specific

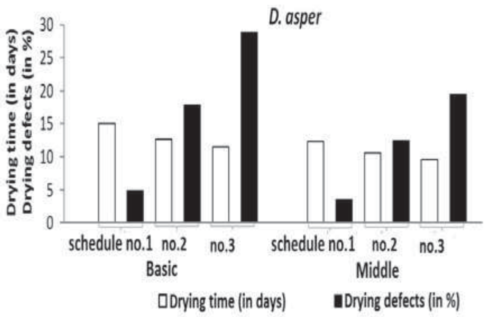

Fig. 8. Drying time and percentage of defects for *D.asper*

gravity 0.46 but its wall thickness is much thicker. In fact, both solid and cavity species have a wide range of structural features and physical properties (specific gravity, moisture diffusion and gas/liquid permeability) that influence the drying behavior.

Drying defects

In kiln drying of bamboo, defects may develop during and after drying. Some common defects are ruptures of culm tissue such as surface checks and splits. Uneven moisture content and discoloration such as mould, blue staining and water staining at the nodes also reduce to drying quality. Most physical defects were end checks, node checks and splits (see Photo 2).

The two cavity species, especially *Dendrocalamus asper* were susceptible to splits, end checks and node checks. The basic part of all species developed more severe defects in comparison to the middle part. The most severe defects in *D. asper* and *B. stenostachya* occurred with the drying schedule no. 3. End splits and node checks lead to 29% defects in basic sections for *D. asper* and to 16% for *Bambusa stenostachya.*

For *B. stenostachya* the slightly milder schedule no. 2 with a final temperature of 65°C and a 20% RH the defect percentage reduced to 5% for the basic and 3 % for the middle parts. Applying the milder schedule no.1 with a low temperature of 55°C and a RH of 30% for *D. asper* minimized defects at the basic to 5% and at the middle 3.5%.

For the solid species *T. siamensis*, the very severe drying schedule no. 4 with high temperature of 75°C and a very low RH of 15% the defect percentage was 6% for the basic and 4% for the middle parts. End checks at internal layer occurred mainly with the basic samples. The solid species *T. siamensis* is easier to dry and less susceptible to defects than the cavity species *B. stenostachya* and *D. asper.*

In drying bamboo, discolourating fungi such as mould and sap staining can grow on green bamboo in kilns operating at a low temperature and high humidity regime (Tang *et al.* 2009). In the drying process using the mild schedule no. 1, mould developed on the basic parts of *D. asper* during the initial stage with a temperature of 45°C and a relative humidity of 80%. Mould was prevented by a high temperature treatment with 80°C and a relative humidity of 90% for 2 hours.

Photo 2: End checks of *T. siamensis* and *D. asper*

CONCLUSION

The initial experiments have shown that kiln drying of bamboo parts can be conducted successfully using proper schedules of temperature and relative humidity. Drying the solid species *Thyrsostachys siamensis* requires a severe drying schedule with high temperature of 65°C and relative humidity of 80% at the initial stage and 75°C with 15% RH at the final step. The drying time was 9 days for the basic and 7 days for the middle sections. The cavity species *Dendrocalamus asper* is a difficult species to dry and susceptible to drying defects and therefore needs a mild schedule with initial temperature of 45°C and initial RH of 80% and a final temperature of 55°C and RH of 30%; the required drying time was 16 days for the basic and 13 days for the middle sections. *Bambusa stenostachya* dried moderately fast using the relative milder schedule with 65°C temperature and 20% relative humidity and resulted in a drying time of 12 days for the basic and 10 days for the middle.

The dry–kiln industry in South Vietnam will apply these effective and feasible schedules for drying longer culms. Additionally, the drying schedules will be further developed for bamboo treated with preservatives based on boron compounds. Since drying is an essential step for processing bamboo into final products, the investigations should also include other commercial species.

ACKNOWLEDGEMENTS

We would like to thank the Duy Quy Company of Mechanical Engineering, Ho Chi Minh–City and the Bamboo Nature Company, Binh Duong Province, Vietnam for providing facilities and materials support for the project. Also thanks to the assistance of Mr. Mai Van Cham, Nong Lam University of HCM and the help of the staff of the Bamboo Nature Company for caring out the pilot experiments.

REFERENCES

Arango, M. J. A. 2006. Trocknungsverfahren fur die Bambusart *Guadua angustifolia* unter tropischen Bedingungen. Dissertation, University Hamburg. pp. 163–184.

Boone, R. S.; Kozlik C. J.; Bois, J.P; Wengert, E. M. 1988. Dry Kiln Schedules for Commercial Woods Temperate and Tropical. General Technical Report FPLGTR- 57. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. pp. 25–26; 37–45.

Hoang, T. T. H.; Tang, T. K. H. 2007. Structural features and physical properties of some important South Vietnam bamboo species. Journal of Agricultural – Forestry Sciences and Technology of Nong Lam University of HCM, (3), 15 – 22.

Keey R. B.; Langrish, T.A.G.; Walker, J. C. F. 2000. Kiln–Drying of lumber. Springer series in Wood Science. Berlin, Heidelberg, New York. 326 pp.

Laxamana M. G. 1985. Drying of some Commercial Philippine Bamboos. FPRDI Journal Volume XIV, (1 & 2), 8–19.

Liese W. 1998. The anatomy of bamboo culms. INBAR Working paper No. 18. International Network for Bamboo and Rattan, New Delhi, India. pp. 102–112.

Pham N. N. 2006. Establishing process of kiln drying for *Bambusa procera* and *B.stenostachya.* Project Report to the Department of Science and Technology of Ho Chi Minh–City, Vietnam. 47 pp.

Simpson W.T 1992. Properties of Wood relative to drying– Dry kiln operators' manual. USDA Agric Handb 188 For Serv For Prod Lab Madison WI. pp. 1–15.

Tang, T.K.H.; Schmidt, O.; Liese, W. 2009. Environment–friendly Short–term Protection of Bamboo against Moulding. Journal Timber Development Association of India, (55), 8–17.

Yosias G. 2002. Preliminary study on the drying of Bamboo *(Bambusa blumeana)* in a wood waste–fired kiln. Bamboo for Sustainable Development. Proceedings of the Vth International Bamboo Congress and the VIth International Bamboo Workshop San Jose, Costa Rica, 2–6 November 1998. International Network for Bamboo and Rattan, New Delhi, India. pp. 495–510.

J Indian Acad Wood Sci
DOI 10.1007/s13196-013-0089-4

ORIGINAL ARTICLE

Kiln drying for bamboo culm parts of the species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*

Thi Kim Hong Tang · Johannes Welling · Walter Liese

Received: 22 January 2013 / Accepted: 1 April 2013

Abstract In South Vietnam *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis* are the major commercial species. Their culms are used for housing and for manufacturing of furniture to export. Our previous study resulted that the kiln drying of 1.4 m culm parts of the bamboos can be conducted successfully using proper schedules defining temperature and relative humidity. In this paper, the effective schedules were further investigated for longer culm parts treated with boron. Culm parts with 2.0 and 2.2 m length after pressure treatment were dried in industrial kilns using three schedules with mild, severe and highly severe drying intensity. The moisture loss, drying time and drying defects were determined. The species *T. siamensis* is the easiest to dry. It takes 8 days for culm parts to reach 10 % starting from an initial moisture content above 120 % with a highly severe drying schedule. *B. stenostachya* dries moderately fast in 10 days using a severe drying schedule. *D. asper* is the most difficult species to dry and requires a mild schedule. It is prone to checking and splitting and needs 13 days of drying.

T. K. H. Tang · W. Liese (✉)
Department of Wood Science, University Hamburg, Leuschnerstr. 91, 21031 Hamburg, Germany
e-mail: wliese@aol.com

T. K. H. Tang
e-mail: tang@holz.uni-hamburg.de

T. K. H. Tang
Faculty of Forestry, Nong Lam University of HCM, Linh Trung, Thu Duc-District, Ho Chi Minh City, Vietnam
e-mail: tangkimhong@hcmuaf.edu.vn

J. Welling
Thünen Institute of Wood Research, Leuschnerstr. 91, 21031 Hamburg, Germany
e-mail: johannes.welling@ti.bund.de

Keywords Kiln drying · *Bambusa stenostachya* · *Dendrocalamus asper* · *Thyrsostachys siamensis*

Introduction

Drying is an important stage of the manufacturing process of bamboo products. Well-dried culms have the desired appearance, finish and structural properties to meet the requirements for the successful export into demanding markets. The drying of bamboo occurs mainly as culm parts. They are round, separated by nodes and inside mostly hollow, called lacuna. At their ends, the metaxylem vessels are the main pathways for releasing moisture. In bamboo the radial passage of moisture is slower than for wood because no ray cells exist (Liese 1998). Generally, the anatomical structure of the bamboo culm makes drying as well as treatment with preservatives more difficult than for wood (Laxamana 1985; Kumar et al. 1994; Liese and Kumar 2003).

Commonly, air-drying has been used since long in rural areas and in small bamboo factories. It has some disadvantages, like long drying time, depending largely on climatic conditions and danger of infection by fungi and beetles. Kiln drying provides a technique for overcoming such limitations. Specially, for large-scale operations kiln drying is more efficient than air-drying and can ensure high quality and continuous supply. With the increasing export of bamboo products, the manufacturers need to expand kiln drying. However, considerable problems exist with drying for the main Vietnamese bamboo species, as no adequate research is available.

So far a few investigations on drying bamboo have been done. Rehman and Ishaq (1947) studied air seasoning of the species *Dendrocalamus strictus, Bambusa arundinacea,*

Published online: 09 April 2013

B. butans and *B. tulda*. A comprehensive investigation on air drying and kiln drying culm parts of several species was done by Glenn et al. (1954), giving a classification of the drying rate into three categories: high, intermediate and low. Laxamana (1985) researched culm parts and splits of *Bambusa vulgaris, Dendrocalamus merillanus, Phyllostachys nigra* and *Schizostachyum diffusum* by air drying and kiln drying and reported that the drying rate is influenced by species as well as the drying condition. Wu (1992) explored high-temperature drying round bamboo of *Phyllostachys makinoi.* Montoya Arango (2006) studied drying round and split bamboo of *Guadua angustifolia* by air-drying, solar drying and kiln drying. In Vietnam, only Pham (2006) investigated kiln drying for *Bambusa procera* and provided some kiln drying schedules for culm parts and splits.

As not much literature is available on drying round bamboo in Vietnam, investigations on the kiln drying of the important commercial species *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis* were done. The three bamboos are distributed in natural stands of South Vietnam, widely planted throughout the country and sufficiently available. Their culms are principally used for constructions and manufacturing of furniture, mainly for export. The previous study on culm parts with 1.4 m length of these species has shown that kiln drying can be conducted successfully with proper drying schedules defining temperature and relative humidity (Tang et al. 2012). In this paper, the drying behaviour of longer culm parts treated with boron was investigated in industrial dry kilns.

Materials and methods

The study was carried out at the factory of the Bamboo Nature Company, Binh Duong province, South Vietnam, from June to October 2009 and from December 2010 to January 2011 in close cooperation with the first author.

Bamboo materials

From the bottom of a culm, parts of 2.0 and 2.2 m length were taken as they are mainly used for products in the Bamboo Nature Company. The skin was removed by machine sanding, which is a common process in bamboo furniture production in Vietnam. Table 1 contains diameter, wall thickness and internode length of the culm parts used for the investigation.

Dry-kiln

The experiments were done in dry kilns of 5.2 m length, 2.7 m height and 3.2 m width. Its heating system was capable of maintaining temperatures up to 80 °C by steam heated coils located vertically near the kiln roof. The relative humidity was adjusted by hot water spraying and venting. The air circulation system consisted of four fans with 60 cm diameter and was reversed every 6 h. The air velocity was maintained at a constant speed of 3.8 m/s. The kiln was operated by an automatic-controller, ensuring the drying schedule by adjusting temperature and relative humidity.

Kiln drying

Culm parts, after boron pressure treatment (Tang and Liese 2011), were stacked with 1.5 cm distance on a kiln car. Each kiln load comprised six cars with one species. To estimate moisture loss, five control samples with their ends sealed with PVA-glue were distributed in two cars nearby the kiln doors. Since these control samples with only 1.6 m length were shorter than the culm parts in the kiln load, this sealing should lead to a similar drying behaviour as in the long culm parts.

During the drying process, the conditions in the kiln were adapted to predefined set-point values. These values were adjusted according to the average moisture content development determined by means of the control samples at various times during the run. To compute the moisture loss, the controls were weighed daily.

Drying schedules

The schedules from the previous experiments (Tang et al. 2012) were applied with three drying intensities: mild, severe and highly severe (Table 2). For each species, two

Table 1 The dimensions of the culm parts tested

Species	Average diameter at the ends (mm)		Average wall thickness at the ends (mm)		Average internode length (cm)	
	Lower	Upper	Lower	Upper	Lower	Upper
T. siamensis	42	35	solid	12	16	28
B. stenostachya	78	74	13	10	25	30
D. asper	82	80	14	12	35	40

Table 2 The conditions (set-point values) of the three drying schedules

Step	Moisture content (%)	Schedule no.1 mild		No. 2 severe		No. 3 highly severe	
		T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	Over 90	50	80	55	80	65	80
2	90–70	50	70	55	75	65	60
3	70–50	60	60	60	65	70	45
4	50–40	60	50	65	50	70	35
5	40–30	60	30	65	35	70	30
6	30–20	65	30	70	25	75	25
7	20–10	65	20	70	20	75	15
Conditioning with 50 °C temperature and 70 % relative humidity							

schedules were tested: schedule no. 1 with mild drying severity for *B. stenostachya* and *D. asper*, schedule no. 2 with severe drying conditions for all three species and schedule no. 3 with highly severe drying conditions only for *T. siamensis*.

Moisture content

The moisture content (MC) was determined by oven drying and calculated as:

$$MC(\%) = \frac{W_{or} - W_o}{W_o} \times 100$$

with W_{or} as original weight of samples and W_o as oven dry weight.

For determination of the average initial moisture content, sections of 10 cm length were cut from both ends of the samples. Five control samples and twenty five further culm parts of each kiln charge were used.

To evaluate the final moisture content and the moisture gradient, sections of 10 cm were taken from both ends and from the middle of 54 culm parts for each kiln charge. The moisture gradient of each culm part (ΔMC) was determined with the following formulae:

$$\Delta MC = MC_m \frac{MC_{e_1} + MC_{e_2}}{2}$$

with MC_m and MC_{e1} MC_{e2} as moisture content of the sections at the middle and the ends of the culm part.

The drying rate was determined by the relationship between moisture decrease and drying time.

Drying defects

All culm parts were visually inspected for defects, like collapse, cracking and splitting. Drying defects were expressed as percentage of all culm parts in each kiln charge.

Results and discussion

Drying rate and drying time

Describing the functional relation of moisture loss over drying time resulted in high coefficients ($R^2 > 98$ %) using regression analysis as shown in Figs. 1, 2 and 3.

The drying rate revealed notable differences between the three species (Fig. 4) as also demonstrated in the previous experiments with shorter culm parts (Tang et al. 2012). The bamboo *T. siamensis* dried fastest, followed by *B. stenostachya* and *D. asper*. This can be explained by the differences in specific gravity and structural features. The oven-dried density of *T. siamensis* ranges from 0.41 to 0.46 g/cm^3, whereas *B. stenostachya* shows a density between 0.65 and 0.72 g/cm^3 and *D. asper* between 0.71 and 0.78 g/cm^3 (Hoang and Tang 2007). Moreover, *T. siamensis* has the shortest internode length (Table 1). The study on bamboo seasoning by Glenn et al. (1954) and Laxamana (1985) concluded for bamboo species with a

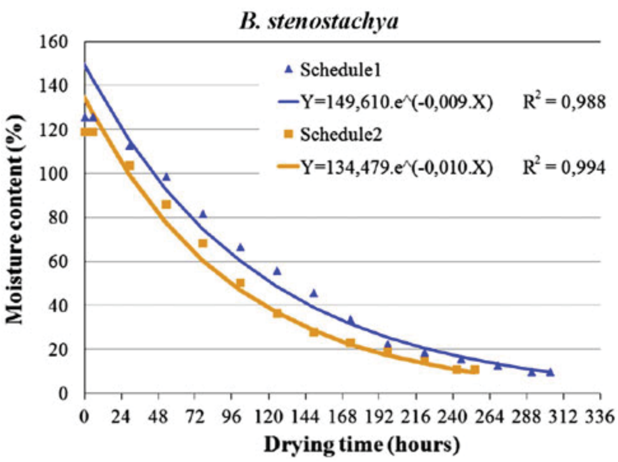

Fig. 1 Relationship between drying time and moisture content of *B. stenostachya*

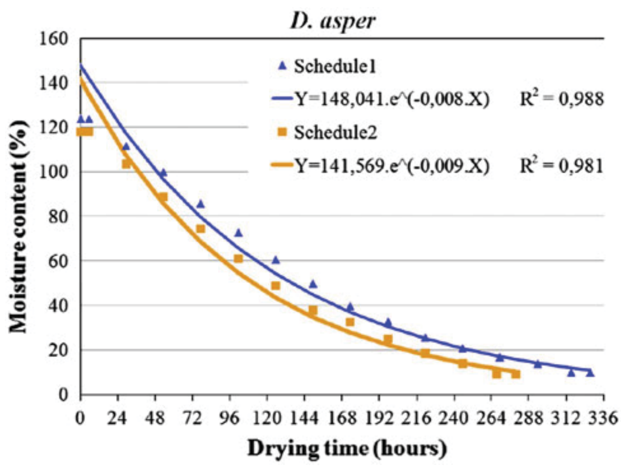

Fig. 2 Relationship between drying time and moisture content of *D. asper*

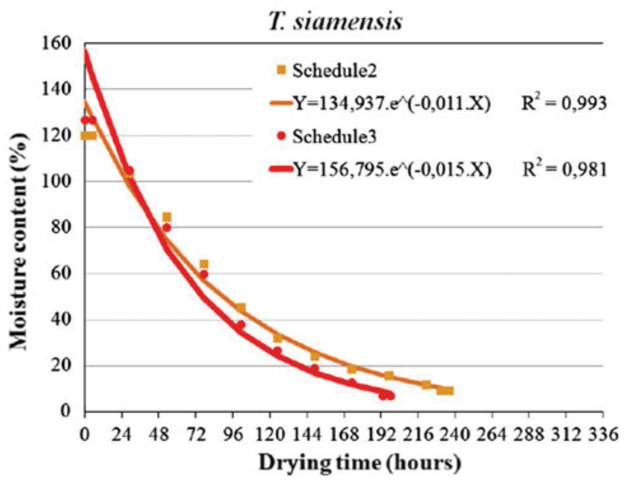

Fig. 3 Relationship between drying time and moisture content of *T. siamensis*

lower specific gravity and shorter internodes a faster drying rate.

With the mild schedule no. 1, the drying time of *B. stenostachya* accounted to 303 h for reducing the initial MC from 125 to 9 %. Bamboo *D. asper* dried in 327 h with a reduction of MC from 120 to 10 %. Schedule no. 1 was not applied for *T. siamensis* as the previous experiments had shown that this species can be safely dried using a more severe drying intensity (Tang et al. 2012).

By applying the severe schedule no. 2, the drying time for *B. stenostachya* was reduced to 254 h and for *D. asper* to 279 h, but for *T. siamensis* 236 h.

The highly severe schedule no. 3 was only used for *T. siamensis* resulting in a drying time of 198 h. This schedule was not applied for *B. stenostachya* and for *D. asper* due to severe defects experienced when applying highly severe drying for shorter culm parts (Tang et al. 2012).

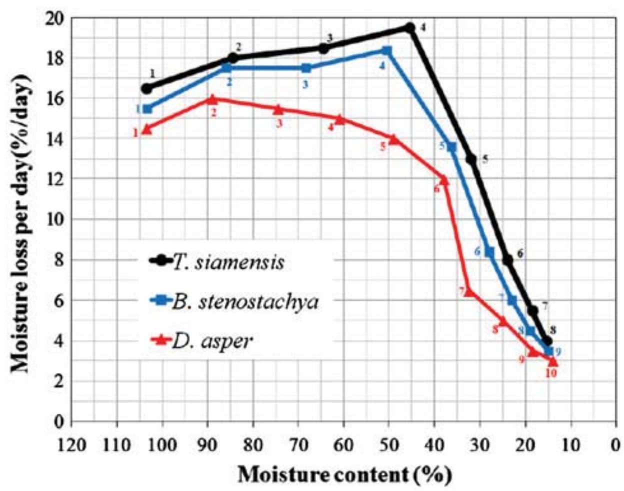

Fig. 4 Drying rate of the three bamboos by the schedule 2

Final moisture content

Table 3 presents the average final moisture content of the three species.

In a large industrial kiln, a variation in final moisture content often exists between culm parts of each drying charge, which can negatively affect the later processing. To reduce such variation, a conditioning period of 12 h was applied for *B. stenostachya* and *D. asper*, but only 5 h for *T. siamensis*.

Comparing the results to the timber drying quality requirements defined in EN 14298 (2004), the final moisture content meets this standard at a target moisture content of 10 % with the schedules no. 1 and 2 for the three bamboos and a target of 7 % with the schedule no. 3 for *T. siamensis.*

Ideally, the moisture distribution within a kiln-dried culm part should be uniform. However, in practice moisture gradients develop by the faster moisture evaporation from the ends and culm surface compared to the diffusion rate from the middle section towards the ends and from the inner culm towards its surface. Results in Table 3 showed that the moisture at the middle section was slightly higher than at the ends. The average moisture gradient for the different kiln runs ranged from 1.0 to 1.3 % with a standard deviation 0.2 to 0.4.

Drying defects

The influence of the drying intensities from mild to severe for defects is shown in Fig. 5. The species *T. siamensis* is less susceptible than *B. stenostachya* and *D. asper*.

With the schedule no. 1 *B. stenostachya* showed 5 % defects and *D. asper* 8 %, mostly as light splits.

Table 3 The average initial moisture content with samples $n = 30$ and the average final moisture content with $n = 54$ of the three bamboos

Species	Schedule	Moisture content (%)							
		Initial		Final					
		Mean	SD	Mean	SD	Min	Max	ΔMC	SD
B. stenostachya	1	125	6.7	10.1	1.1	7.2	11.4	1.1	0.3
	2	119	7.4	9.6	0.8	6.7	10.5	1.0	0.2
D. asper	1	124	7.2	10.2	1.0	8.1	11.7	1.2	0.3
	2	118	8.9	9.3	1.4	7.6	12.1	1.3	0.4
T. siamensis	2	120	7.8	9.8	1.3	7.4	10.9	1.1	0.2
	3	127	5.8	6.9	1.2	5.1	8.9	1.3	0.3

SD standard deviation, *ΔMC* gradient of moisture content

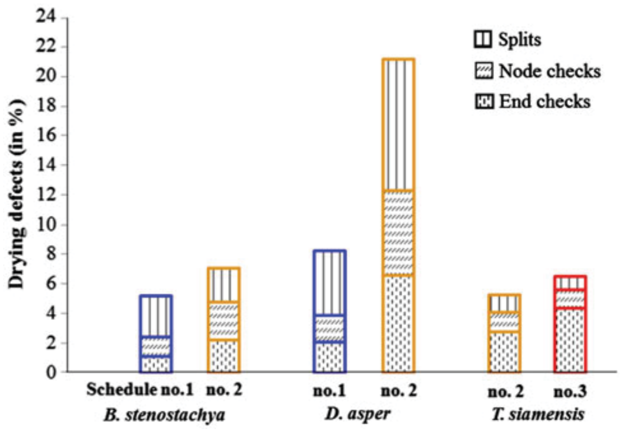

Fig. 5 Drying defects of the three bamboos

While applying the schedule no. 2 for *D. asper*, 21 % of the culm parts exhibited defects, but for *B. stenostachya* only 7 % and for *T. siamensis* 5 %. The bamboo *D. asper* was liable to splits, end checks and node checks.

Using the schedule no. 3 for *T. siamensis* 6.5 % of the culm parts showed mostly end checks at the internal layer.

Comparison of the drying results of the boron treated culm parts and the untreated ones from the previous experiments revealed that the formers had less splits. Similarly, Sharma et al. (1972) recommended a chemical pre-treatment of round bamboo to prevent the occurrence of splitting. These observations need further studies.

In drying bamboo, discolourating fungi can grow at high moisture content in kilns operating at low temperature and high humidity. As being shown in the previous experiments (Tang et al. 2012), the application of a low temperature schedule of 40 °C and a relative humidity of 85 % during the initial stage of drying led to mould development on culm parts of *D. asper*. Mould was prevented by an initial phase with 80 °C and a relative humidity of 90 % for 2 h.

Conclusions

Kiln drying of bamboo culm parts treated with boron can be applied successfully using suitable schedules of temperature and relative humidity. All drying schedules investigated for the three species meet the specification for the final moisture content in EN 14298 (2004). Considering practical points for reducing seasoning time and defects, the following drying schedules are recommended:

Bambusa stenostachya dried moderately fast using a severe schedule with an initial temperature of 55 °C and RH of 80 % and a final temperature of 70 °C and 20 % RH for 10 days.

Dendrocalamus asper is a difficult species to dry and susceptible to drying defects. It therefore needs a mild schedule with initial temperature of 50 °C and RH of 80 % and a final temperature of 65 °C and RH of 20 % for 13 days.

Thyrsostachys siamensis is easy to dry applying a highly severe drying schedule with temperature of 65 °C at initial stage and relative humidity of 80 % and towards the end with 75 °C and 15 % RH for 8 days.

As a consequence of the results achieved by this study, South Vietnamese bamboo processing companies with kiln drying facilities, like Bamboo Nature Company and Bamboo Villages Co., have already applied these effective schedules for drying boron treated culm parts. The drying schedules should be further investigated for bamboo treated with CCB as well as other commercial species, such as *Bambusa vulgaris* and *Dendrocalamus barbatus*.

Acknowledgments We would like to thank the Bamboo Nature Company and its staff, Binh Duong Province, Vietnam, for caring out the experiments. We also thank for the assistance of Ms. Ho Thuy Dung, at the Centre of Research and Transfer of Technology for Forest Products Processing, Nong Lam University of Ho Chi Minh City, Vietnam.

References

EN 14298 (2004) Sawn timber-assessment of drying quality. European Committee for Standardization, p 1–8

Glenn HE, Brock DC, Byars EF et al (1954) Seasoning, preservative treatment and physical property studies of bamboo. Clemson, South Carolina Bulletin No.7, p 27–36

Hoang TTH, Tang TKH (2007) Structural features and physical properties of some important South Vietnam bamboo species. J Agric For Sci Technol Nong Lam Univ of HCM 3:15–22

Kumar S, Shukla KS, Dev I, Dobriyal PB (1994) Bamboo preservation techniques: a review. International Network for Bamboo and Rattan (INBAR) and Indian Council of Forestry Research Education (ICFRE), p 18–19

Laxamana MG (1985) Drying of some commercial Philippine bamboos. J For Prod Res Dev Instit Philipp FPRDI 14(1 & 2):8–19

Liese W (1998) The anatomy of bamboo culms. INBAR Tech Rep 18:152–161

Liese W, Kumar S (2003) Bamboo preservation compendium. INBAR Tech Rep 22:82–87

Montoya Arango JA (2006) Trocknungsverfahren für die Bambusart *Guadua angustifolia* unter tropischen Bedingungen. Dissertation University Hamburg

Pham NN (2006) Establishing process of kiln drying for the bamboo Lo o and the rattan Song may. Department of Science and Technology of Ho Chi Minh-City, Vietnam, Research Report, No. 11

Rehman MA, Ishaq SM (1947) Seasoning and shrinkage of bamboo. For Res Inst Dehra Dun India 4(2):1–20

Sharma SG, Tewari MC, Sharsa RD (1972) Chemical seasoning of bamboo in the round for handicrafts. J Timber Dev Assoc India 13(1):17–23

Tang TKH, Liese W (2011) Pressure treatment of the Vietnamese common bamboos with boron and CCB. J Bamboo Rattan 10(1&2):1–12

Tang TKH, Welling J, Ho TD, Liese W (2012) Investigation on optimization of kiln drying for the bamboo species *Bambusa stenostachya, Dendrocalamus asper* and *Thyrsostachys siamensis*. J Bamboo Sci Cult 25(1):27–35

Wu KT (1992) The effect of high-temperature drying on the anti-splitting of makino bamboo culm (*Phyllostachys makinoi* Hay.). J Wood Sci Technol 26:271–277