THE GLUABILITY AND BONDING QUALITY OF AN ASIAN BAMBOO (*DENDROCALAMUS ASPER*) FOR THE PRODUCTION OF COMPOSITE LUMBER

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Received December 2008

MALANIT P, BARBU MC & FRÜHWALD A. 2009. The gluability and bonding quality of an Asian bamboo (*Dendrocalamus asper*) for the production of composite lumber. The aim of this research was to determine the fundamental properties of *Dendrocalamus asper* and its suitability to be promoted as a raw material for the manufacture of composite lumber. The parameters studied were pH value, buffer capacity and bonding quality of bamboo strands using different adhesives. The pH and acid-buffering capacity, measured at three locations along the culm length, were 5.4 and 0.53 milliequivalents respectively. However, values from the different locations in the culm did not show any significant difference. The bonding quality of the bamboo strands was evaluated for three adhesives using a special device called an Automated Bonding Evaluation System (ABES). Three essential parameters were studied, namely, three types of glues (melamine formaldehyde, melamine urea phenol formaldehyde and phenol formaldehyde), four pressing temperatures (150, 170, 190 and 210 °C) and different pressing times (20 to 300 s). It was observed that bond quality was improved by increasing the hot pressing time and temperature. Results also showed that melamine formaldehyde was the best adhesive to bond bamboo strands.

Keywords: Adhesive, pH, buffer capacity, bamboo quality, structural composite lumber

MALANIT P, BARBU MC & FRÜHWALD A. 2009. Perekatan dan kualiti pengikatan buluh Asia (*Dendrocalamus asper*) dalam penghasilan kayu komposit. Tujuan kajian ini adalah untuk menentukan ciri asas *Dendrocalamus asper* dan kesesuaiannya untuk dijadikan bahan mentah dalam pengeluaran kayu komposit. Parameter yang dikaji ialah nilai pH, muatan penimbal dan kualiti pengikatan lembar buluh apabila perekat yang berbeza digunakan. Nilai pH dan muatan penimbal asid yang disukat pada tiga tempat berlainan sepanjang kulma masing-masing ialah 5.4 and 0.53 milisetara. Namun, nilai yang diperoleh daripada ketiga-tiga tempat tersebut tidak menunjukkan sebarang perbezaan signifikan. Kualiti pengikatan lembar buluh dinilai untuk tiga jenis perekat menggunakan Sistem Penilaian Pengikatan Automatik (ABES). Tiga parameter penting dikaji iaitu tiga jenis perekat (melamin formaldehid, melamin urea fenol formaldehid dan fenol formaldehid), empat suhu tekanan (150 °C, 170 °C, 190 °C dan 210 °C) dan tempoh tekanan (20 saat hingga 300 saat). Hasil kajian menunjukkan bahawa kualiti pengikatan ditambah baik dengan meningkatkan tempoh serta suhu tekanan. Keputusan juga menunjukkan bahawa melamin formaldehid merupakan perekat terbaik untuk mengikat lembar buluh.

INTRODUCTION

In recent years, the demand for high quality wood for construction has increased because the world population has been rising especially in Asia and Latin America and the available quantity and quality of wood from natural forest have been declining. Consequently, the search for non-wood resources as alternative to wood has been accelerated. Bamboo is a non-wood lignocellulosic material which has been widely used for thousands of years in tropical countries as a material for construction, furniture manufacture and daily household uses such as for chopsticks, music instruments and handicrafts. It is now also widely used as a raw material for pulp and paper, plywood, medium density fiberboard (MDF), particleboard and oriented strand board (OSB) due to its high strength and other favourable properties.

Bamboo culms are generally cylindrical and hollow. The outer part of the culm is covered by a cutin layer with a wax coating on top, while the inner part consists of parenchyma cells and vascular bundles. The waxy outer layer cuticle is harder to glue than the inner layer of the culm (Lee *et al.* 1996).

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The specific gravity of wood species directly influences the strength of wood composite. Adhesives are used to hold wood particles together. Mechanical interlocking occurs when an adhesive penetrates and cures on the wood surface. Denser wood species are more difficult for adhesives to penetrate. The small size of their lumens, their thick walls and narrow pit openings between fibres restrict adhesive flow into the wood and usually result in shallow adhesive penetration. Such shallow penetration produces inadequate bonding, resulting in a low quality product.

Melamine formaldehyde (MF), melamine urea phenol formaldehyde (MUPF) and phenol formaldehyde (PF) are typically used in the manufacture of products requiring some degree of exterior exposure durability, for example, OSB, plywood, and siding panels. MF resin is a thermosetting resin made from melamine and formaldehyde by polymerization. It is four times more expensive than urea formaldehyde (UF) and is used to upgrade the latter by improving its weathering resistance. MUPF resin is a co-polycondensation resin of melamine, urea, phenol and formaldehyde and is used to make particleboard and OSB for exterior and bearing applications. PF resin is a synthetic thermosetting resin, which is obtained by the reaction of phenols. PF resin is widely utilized in wood-based panel industries for high quality plywood, OSB, laminated veneer lumber (LVL), mineral wool (insulation), technical and decorative laminates.

Chemical composition

The main constitutes of bamboo culms are cellulose, hemicellulose and lignin while the minor, resins, tannins, waxes and inorganic salts. Chemical properties vary according to species, growing conditions, age and site of growth of the bamboo culm (Liese 1985). A three-year-old *Dendrocalamus asper* contained 68% cellulose and 29% lignin apart from ash (1.5%), alcohol-benzene soluble (6%), hot-water soluble (8%), cold-water soluble (7%) and 1% NaOH soluble (25%) materials (Kamthai 2003). The author also showed that nodes contained more lignin and ash but less water soluble extractives than the internodes. The top part of the culm has significantly higher extractive and ash contents than the middle and bottom parts, which have similar amounts. In the radial direction, the ash content is higher in the inner than in the outer part, while it is lowest in the middle part. The ash content of bamboo is mostly made up of inorganic minerals, primarily silica, calcium and potassium. Higher ash content in bamboo can adversely affect tool wear during machining (Abd Latif 1993).

As with other wood species, cellulose, hemicellulose and lignin in *D.* asper is over 90% of its total mass. A change in raw material mix, however, may affect the physical and mechanical properties of the boards and require further adaptation of the processing conditions, e.g. the adhesive system. The adhesive is a significant cost factor in panel production, being about 20% of total production cost and, unfortunately, is not in abundant supply in regions where bamboo is currently available. Future development of bamboo-based composites will require a thorough analysis of bamboo gluability and of the bonding quality of its strands.

pH and buffer capacity

The gluability of wood is influenced by its surface properties, such as roughness, pH and buffering capacity. The acidity of most woods is caused by free acids and acidic groups which are present in extractives and noncellulosic polysaccharides and are easy to split off. Common wood species are usually acidic. Woods from temperate zones have pH levels in the range of 3.3–6.4, while tropical woods have pH levels in the range of 3.7–8.2 (Fengel & Wegener 1984).

Buffer capacity is the resistance of wood to change in its pH level. Wood that requires a large amount of acid catalyst to decrease the pH to the level required for optimum adhesive cure is considered as a high buffering capacity species (Maloney 1993). Wood pH and buffer capacity strongly influence curing time and bonding strength of UF resins (Park *et al.* 2001). Adhesive curing time and its bond strength decreased with the increased wood pH and buffer capacity. The catalyst buffering action also has strong effects on hardening speed, degradation reactions and the degree of networks formed by MUF resin (Zanetti & Pizzi 2003). It was reported that the acidity of *Eucalyptus grandis* strongly resisted the curing of PF and tannin adhesives during the hot-pressing of exterior particleboard (Van Niekerk & Pizzi 1994).

In order to obtain high bonding strength, pressing parameters must be adjusted according to the pH conditions encountered. If this is neglected, the glue line will be either uncured or over-cured, resulting in poor bonding strength. Thus, pH and buffering capacity measurements of raw materials are fundamental to determine optimum pressing parameters (the pressing time and temperature) for panel manufacturing. Understanding these properties is important when discussing the compatibility of bamboo as a raw material for oriented strand lumber (OSL) or OSB manufacture. Therefore, the objectives of this study were to (1) measure and compare mean pH value and buffer capacity in each location of *D. asper* culms and (2) investigate the strength development characteristics and bonding quality between bamboo strands using different adhesives for exterior application.

MATERIALS AND METHODS

Some of these investigations were done at the Wood Science and Engineering Research Unit, Walailak University in Nakorn Sri Thammarat, Thailand and the rest in the Department of Wood Science, University of Hamburg, Germany.

Materials

Three *D. asper* culms for this study were collected in April 2007 from plantations located in Nakorn Sri Thammarat, south of Thailand. Three culms (3 years old) were harvested and transported to the Wood Science and Engineering Research Unit, Walailak University in Thailand for future investigation. These bamboos had an average culm length of 19 m. The culm diameter at the bottom was about 11.5 cm, while the top culm, about 2 cm. Average culm wall thickness was 1.6 cm and average specific gravity at 12% moisture content was 0.75.

Each culm was divided into three sections, each 6 m long, and categorized according to height, namely, bottom, middle and top. Specimens were obtained from each of these three parts. Bamboo chips from each part were ground into particles by a Wiley machine. The samples were then placed in a shaker with sieves of 40-mesh screen (0.425 mm diameter) and retained on a 60-mesh screen (0.250 mm diameter). Particles remaining on the 60-mesh screen were used for the measurement of pH value and buffer capacity.

Three adhesives were used in this research, namely, MF, MUPF and PF. The MF resin (13H560, liquid) was supplied by Dynea. The MUPF resin (KML 534, liquid) was obtained from BASF and the PF resin (Bakelite 1279 HW, liquid), from Hexion Specialty Chemicals GmbH. Their characters are presented in Table 1.

Measurement of pH value

The pH measurement procedure was adapted from the measurement of hydrogen ion concentration (pH) of paper extracts by cold extraction method, TAPPI T 509 om-83 (Anonymous 1983). One gram of specimen was transferred into a 100 ml beaker and distilled water (pH ~6.7) was added to bring the total volume to 70 ml. The mixture was stirred and allowed to soak for one hour at room temperature (20 °C). A pH meter (Type WTW pH 330i) was used for the measurement. The pH value was recorded when there was no more drift in the measurement for a period of 30 s. Each specimen was conducted using three replications. Analysis of variance (ANOVA) was performed to determine differences between means and Duncan's multiple range test (DMRT) was used for the comparison procedure.

Buffer capacity measurement

The buffer capacity measurement procedure was adapted from the method used by Maloney and Borden Chemical Inc. (Maloney 1993). A total of 30 g dry specimen was soaked in 400 ml

Table 1 Some characters of the three glues used in the experiment

Character	Glue type		
	MF	MUPF	PF
Colour	Brown	Pale brown	Red brown
Solid content (%)	62.5	64.0	48.0
pH at 20 °C	9.73	9.3–9.8	8.5–10.5
Viscosity at 20 °C (mPa s)	133	150–400	650–700

distilled water at 20 °C for 30 min. The mixture was continuously stirred during soaking. The liquid was then decanted into a Buchner (Coors) filter no. 2 containing a Whatman filter paper no. 4. Using vacuum, the liquid was drawn though the filter paper and 150 g of the liquid was placed in a 400-ml beaker and its pH was recorded. Sulphuric acid (0.01 N) was next added to the liquid in small increments of 5 ml each. The liquid was then mixed by a magnetic stirrer and the pH was measured each time after acid was added, until a reading of 3.5 was reached. The number of milliequivalents (N × ml; where ml = volume in ml and N = normality) of acid needed to change the pH to 3.5 was calculated as the buffer capacity. Each measurement was conducted in three replications. For statistical analysis, ANOVA was performed and DMRT was used for the comparison procedure.

Bonding quality

Bonding quality was measured using the Automated Bonding Evaluation System (ABES), which was designed to determine the strength development characteristics of adhesives. With this system, effects of pressing temperature and time on the strength development rate of thermosetting adhesives can be characterized.

Bamboo strands (12.0 × 2.0 cm, 0.7 mm thick) were obtained from bottom internodes which had culm wall thicknesses > 2.0 cm. The strands were kept in a conditioning chamber at a temperature of 20 °C and relative humidity of 65% to a final average moisture content of 12%.

All adhesives (MF, MUPF and PF) were blended according to the specifications of their suppliers. The adhesive was then spread on one surface (5 × 10 mm) of the bamboo strand with a hand brush. A spread rate of approximately 200 g m^{-2}, single glue line, was used. The outer layer of the bamboo culm is harder to glue than the inner layer. Hence, two bamboo strands were placed in the ABES bond pressing zone with grains of both strands parallel to each other in an outer-layer-to-inner-layer configuration. After lay up, the strands were hot-pressed under controlled parameters of temperature (150, 170, 190 and 210 °C), time (20 to 300 s, in 20 s steps) and pressure (4 N mm^{-2}). Immediately after each bond was cured to the required level, it was tested to destruction in shear mode according to the ASTM standard test method D-3165-07. Tensile load and gripping head movement (sample elongation) were PC-monitored during the pulling of strand and shear stress at failure was calculated. The operation manner of set up is described in Figure 1.

RESULTS AND DISCUSSION

pH value

The pH value of *D. asper* is on the acidic side, with mean values for bottom, middle and top sections of the culm being 5.36, 5.45 and 5.38 respectively (Table 2). However, there was no significant difference in pH values between the sections (F-value = 0.23). The pH value of *D. asper* is quite similar to European beach (Fengel & Wegener 1984).

The pH value of raw material is very important for the various ranges of its utilization. The cross-linking rate of most thermosetting adhesives used in wood composite manufacturing depends on pH levels. Thus, the acidity of particles and the catalyst which are added into the adhesive plays a very important role in providing an optimum

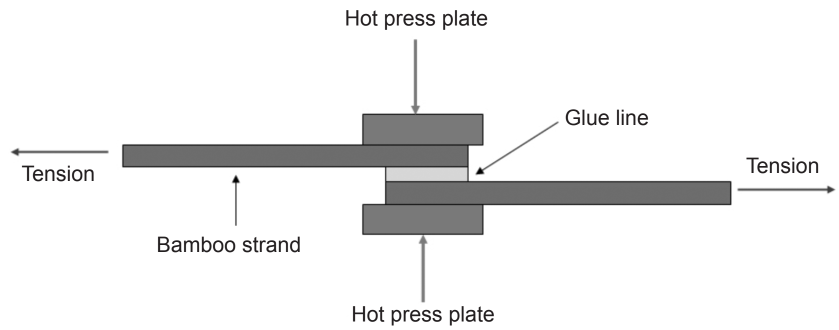

Figure 1 Schematic description of shear test by Automated Bonding Evaluation System (ABES)

Table 2 The pH values and buffer capacity in each section of the culm of *Dendrocalamus asper*

Value	Culm locations		
	Bottom	Middle	Top
pH	5.36 a	5.45 a	5.38 a
Buffer capacity (me.)	0.58 b	0.54 b	0.48 b

Means with the same letter within a row are not significantly different at $p < 0.05$.

condition during resin curing. For species with higher pH levels, additional catalyst is needed to properly cure the resin during hot pressing.

It is desirable that the pH of *D. asper* be close to common wood species. Since, *D. asper* in this study has no variation in pH values at the different sections on the culm, the same technology and practices applied for other wood species may be applied to this bamboo species when being used as an alternative raw material in composite manufacturing.

Buffer capacity

The acid-buffering capacity of *D. asper* at three different sections of the culm is illustrated in Table 2. The average buffer capacity of bottom, middle and top parts of the culm are 0.58, 0.54 and 0.48 milliequivalents respectively. Although there were no significant differences between sections (F-value = 0.27), the value gradually decreased from bottom to top of the culm. The lower parts of culms have more extractives and this contributes to a higher acidity. It is known that bamboo extractives have some variation in their vertical location (Liese 1985). The lower part of the culm has significantly higher extractive contents, particularly with hot water and 1% NaOH extracts compared with the rest of the parts (Liese 1985).

The pH values of *D. asper* during the addition of acid is illustrated in Figure 2. It is evident that *D. asper* had extremely high resistance to changes in the pH and weakly responded to the acid addition (sulphuric acid) when compared with normal mixed wood. *Dendrocalamus asper* needed five times the amount of acid which was required for wood to achieve a pH of 3.5.

The acid-buffering capacity of *D. asper* is high when compared with wood species. A high buffer capacity species needs a large amount of acid catalyst to reduce the pH to optimum level which is required for a resin cure. This may cause problems for *D. asper* if used as raw material in wood composite with conventional commercial resin. Some strategies, such as the use of special glue to produce boards or adjusted hot-pressing parameters, may be applied to improve resin curing and, hence, improve product properties too. Nevertheless, this will also mean that the production costs will increase.

Although differences in buffer capacities were not significant, the values varied along culm locations. Thus, it should require some special

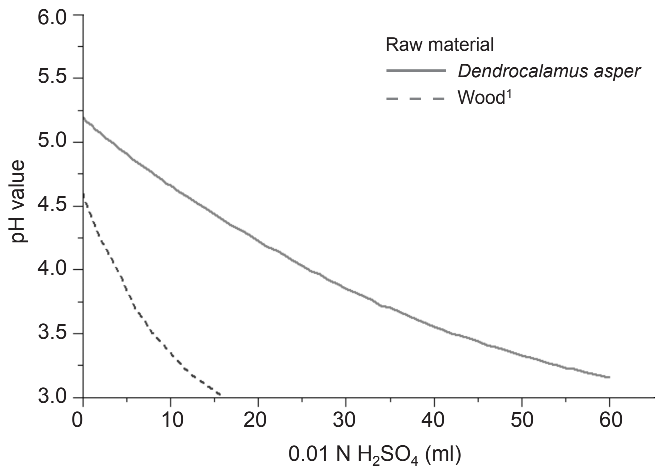

Figure 2 pH changes of *Dendrocalamus asper* and wood during acid addition; [1]Sauter (1996)

consideration in regard to catalyst addition and resin cure, i.e. a special glue of adjusted hot-pressing parameters is needed.

Bonding quality

Figures 3, 4 and 5 present results of shear strength which is related to pressing times and pressing temperatures for bamboo strands which were glued with MF, MUPF and PF respectively.

Influence of pressing temperature and time

Results of ABES tests indicated that bonding strength of glue line varied significantly with different pressing temperatures and times. The maximum value of shear strength was 8.54 N mm^{-2} for MF resin at 170 °C and 200 s (Figure 3), while the minimum was 0.31 N mm^{-2} for MUPF resin at 150 °C and 20 s (Figure 4).

The higher the pressing temperature, the greater the rate at which adhesive bonds develop and, thus, the higher the shear strength. At low pressing temperatures, the bonding strength is limited because the resin cannot completely cure, but an excess temperature can reduce bonding strength in the glue line as illustrated at 190 and 210 °C for MF and MUPF resins respectively (Figures 3 and 4) and 210 °C for PF resin (Figure 5).

Results also indicated that bonding quality varied significantly with different pressing times. Notably, shear strength reached it peak in the middle phase of the pressing time and dropped thereafter (Figures 3–5). Overlong pressing time will reduce the completed adhesive bonding in the glue line. However, bonding strength developments at the excess temperatures (190 and 210 °C for MF and MUPF respectively and 210 °C for PF) behaved differently. They were rather constant and showed lower shear strength values than the rest of the measurements. PF resin requires higher press temperature for condensation reaction (Blomquist *et al.* 1983). Nevertheless, this is a laboratory study and further study is required to explore this research in an accurate parameter at an industrial scale.

Pressing temperature also affected the pressing time. At lower temperature, a longer pressing time was needed to reach the maximum bonding strength (Figure 3). At 150 °C, the maximum shear strength was 7.84 N mm^{-2} at 300 s pressing time, while the maximum shear strength for 170 °C is 8.57 N mm^{-2} at 200 s pressing time.

Influence of resin types

The three adhesives which were evaluated in this study showed different maximum shear strengths. Highest shear strength values for MF, MUPF and PF were 8.54, 7.23 and 7.29 N mm^{-2} respectively (Figures 3–5). The values did not show any effect with pressing time, hence almost all of the relations were parabola graphs. The adhesives used were all thermosetting resins and although their cross-linking reactions took place in the bond under applied pressure and heat, their network bonding could be attacked by excess temperature. It is important to note that adhesive types vary significantly in bonding conditions for which they require in use, especially with regard

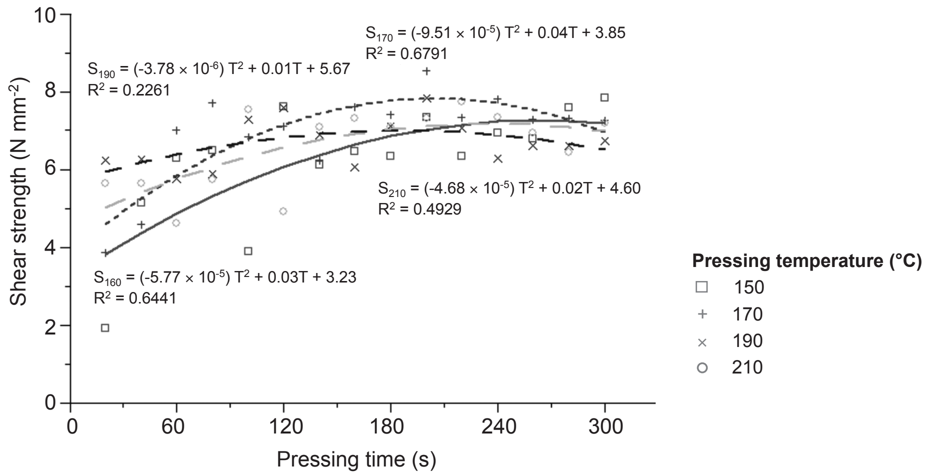

Figure 3 Shear strength of MF-glued bamboo strands as a function of pressing time and temperature

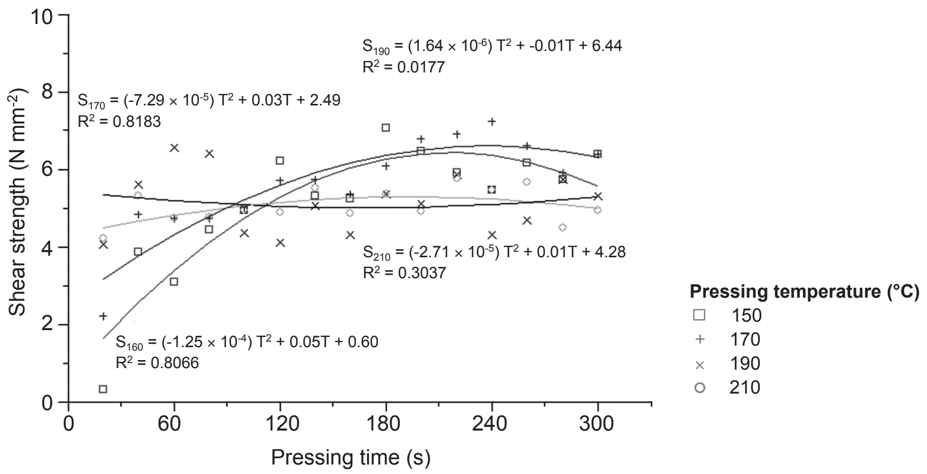

Figure 4 Shear strength of MUPF-glued bamboo strands as a function of pressing time and temperature

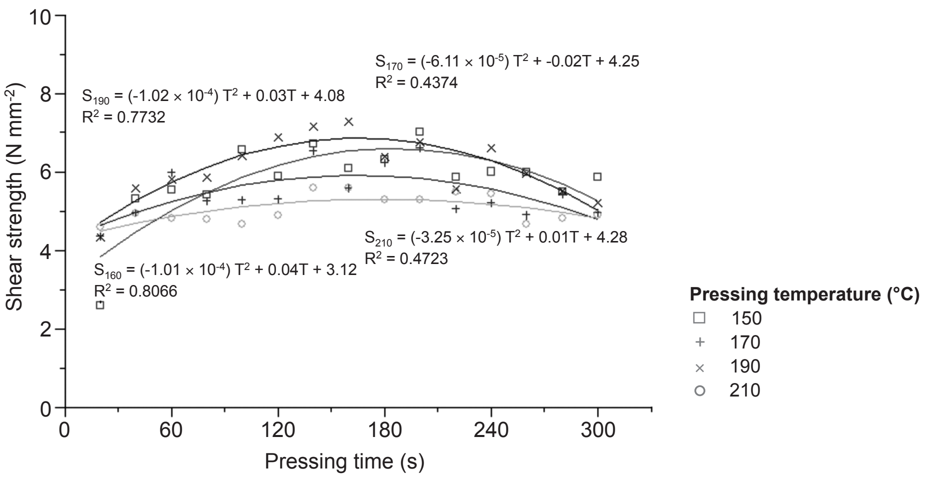

Figure 5 Shear strength of PF-glued bamboo strands as a function of pressing time and temperature

to temperature and time. MF and MUPF could harden and bond properly at lower temperature (170°C) while PF required higher temperature (190 °C).

CONCLUSIONS

The pH value, buffer capacity and bonding quality of *D. asper* strands have been analysed. *Dendrocalamus asper* had a comparable pH value with other wood species and the value did not vary along the location of the culm. Buffering capacity of *D. asper* strands was higher than those of other wood species. The bond strength between bamboo strands and adhesive was improved by increasing the hot pressing time and temperature. The adhesives studied exhibited satisfactory bond quality for glue lines in bonding of bamboo strands but the best adhesive was MF. Future works in this area should determine the alkali buffer capacity of *D. asper,* the relationship between buffer capacity and chemical composition of *D. asper,* the resin gel time and the effect of the bamboo on resin gel time of each glue.

ACKNOWLEDGEMENTS

We gratefully acknowledge the German Academic Exchange Service (DAAD) and the Department of Wood Science/Mechanical Wood Technology, University of Hamburg, Germany for financial support. We would also like to express our thanks to the Department of Wood Science/Mechanical Wood Technology, University of Hamburg, and the Wood Science and Engineering Research Unit, Walailak University, Thailand for providing facilities for the experimental work.

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