PROPERTIES OF GLUE-LAMINATED TIMBER MANUFACTURED FROM VISCOELASTIC-THERMAL COMPRESSION MODIFIED *Paraserianthes falcataria* LAMINAS

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DECLARATION

I hereby declare that the material in this thesis is my own except for equations, summaries and references, which have been duly acknowledged.

17 February 2022

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Assoc. Prof. Ts. Dr. Liew Kang Chiang

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ABSTRACT

Shortage in timber supply is a major concern for wood-based industry since the last two decades, where the existing medium-heavy hardwood have long rotation age. *Paraserianthes falcataria* is a fast-growing tree species that have short-rotation age, but possessed poor physical and mechanical characteristics, which limits its range of application. However, these properties can be improved by densification. Previous studies reported that densification technology had enhanced the density and mechanical strength of wood. Therefore, in this study, laminas from *Paraserianthes falcataria* underwent viscoelastic-thermal compression (VTC). This study evaluated (1) the physical and anatomy properties of the VTC modified laminas, (2) the physical and mechanical properties of glulam manufactured from VTC modified laminas, and (3) the relationship between properties of the VTC modified laminas and glulam. During VTC treatment, the laminas were pre-steamed, compressed with heat, and underwent cooling phase. Five different parameters, including control, were applied, denoted as S1/D (10 minutes pre-steamed, densified), S2/D (20 minutes pre-steamed, densified), S3/D (30 minutes pre-steamed, densified), NS/D (non-pre-steamed, densified), and control (NS/ND: non-pre-steamed, non-densified). VTC modified laminas were also processed to make glulam panels. The outcome from lamina tests showed that S1/D had the highest density (density: 623.30 kg/m^3, density profile: 590.22 kg/m^3) whilst having the lowest moisture content (7.64%) and springback rate (0.71%). Besides that, S1/D also achieved the lowest contact angle (water: 11.78°, polyvinyl acetate: 74.72°), which indicated good wettability for bonding purpose. In contrast, morphological analysis revealed that S3/D had the highest rate of cell lumen deformation (39.61 μm^2), which is supposed to be indicative of higher density and contact angle. As for the physical properties of glulam, S2/D acquired the highest water absorption and thickness swelling with values of 106.49% and 50.87%, respectively. On the other hand, S3/D had the lowest values in those tests, and obtained the highest delamination rate (73.97%). In relation to morphological analysis, a higher rate of cell lumen deformation reduced the water absorption and decrease the bonding efficiency. Despite of having poor physical properties, the glulam of S3/D obtained the highest resistance against elastic deformation and rupture, as indicated by the findings from static bending and compression tests. S1/D, on the other hand, have the highest shearing strength (2.89 N/mm^2) and hardness (radial: 1986.00 N, longitudinal: 2953.20 N). The correlation analysis showed that the MOE (edgewise) and density profile of lamina of S3/D have a significant, highly strong positive relationship. In summary, VTC treatment enhanced the physical properties of *Paraserianthes falcataria* laminas by 49.16%, while physical and mechanical properties of glulam were also improved by 45.71% and 50.08%. The treatment also reduced the cell lumen area by 49.51%. 10 minutes of pre-steaming was the ideal duration to increase the physical properties of laminas and glulam, while 30 minutes of pre-steaming have remarkably enhanced the mechanical properties. The correlation analysis indicated that increase in density of lamina enhanced the mechanical strength of glulam, where 30 minutes of pre-steaming showed a significant positive relationship.

ABSTRAK

CIRI-CIRI GLULAM DIHASILKAN DARIPADA LAMINA *Paraserianthes falcataria* YANG DIMODIFIKASI MELALUI RAWATAN PEMAMPATAN VISKOELASTIK-TERMAL

Kekurangan bekalan kayu ialah kebimbangan utama untuk industri berasaskan kayu sejak dua dekad lalu, yang mana kayu keras sederhana-berat sedia ada mempunyai tempoh kitaran yang panjang. Paraserianthes falcataria ialah spesies pokok cepat tumbuh yang mempunyai tempoh kitaran pendek, tetapi mempunyai ciri-ciri fizikal dan mekanikal yang lemah. Namun, ciri-ciri tersebut mampu dipertingkatkan dengan pemampatan. Kajian terdahulu melaporkan bahawa teknologi pemampatan telah meningkatkan ketumpatan dan kekuatan mekanikal pelbagai spesies kayu. Oleh itu, dalam kajian ini, lamina dari Paraserianthes falcataria telah menjalani rawatan pemampatan viskoelastik (VTC). Kajian ini menilai (1) ciri-ciri fizikal dan anatomi lamina dimodifikasi melalui VTC; (2) ciri-ciri fizikal dan mekanikal glulam dihasilkan dari lamina dimodifikasi melalui VTC, dan (3) hubungan antara lamina dimodifikasi melalui VTC dan glulam. Semasa rawatan VTC, lamina telah dikukus, dimampatkan dengan haba, dan menjalani fasa penyejukan. Lima parameter berbeza, termasuk kawalan, diaplikasikan dan dilabelkan sebagai S1/D (dikukus 10 minit, dimampatkan, S2/D (dikukus 20 minit, dimampatkan), S3/D (dikukus 30 minit, dimampatkan), NS/D (tidak dikukus, dimampatkan), dan kawalan (NS/ND: tidak dikukus, tidak dimampatkan). Lamina dimodifikasi melalui VTC juga telah diproses untuk membuat panel glulam. Hasil dari ujikaji lamina menunjukkan bahawa S1/D mempunyai ketumpatan tertinggi (ketumpatan: 623.30 kg/m^3, profil ketumpatan: 590.22 kg/m^3), di samping mempunyai kandungan lembapan (7.64%) dan kadar pemulihan (0.71%) terendah. Selain itu, S1/D juga mencapai sudut kontak terendah (air: 11.78°, polivinil asetat: 74.72°), yang menunjukkan kebolehbasahan yang baik untuk tujuan perekatan. Sebaliknya, analisis morfologi mendedahkan bahawa S3/D mempunyai kadar deformasi sel lumen tertinggi (39.61 µm^2), yang sepatutnya menunjukkan ketumpatan dan sudut kontak yang lebih tinggi. Untuk ciri-ciri fizikal glulam, S2/D masing-masing memperoleh penyerapan air, dan pembengkakan ketebalan tertinggi iaitu 106.49% and 50.87%. Sebaliknya, S3/D mempunyai nilai terendah dalam ujian-ujian tersebut, dan mendapat kadar delaminasi tertinggi (73.97%). Berhubung dengan analisis morfologi, kadar deformasi sel lumen yang lebih tinggi akan mengurangkan penyerapan air dan kecekapan perekatan. Walaupun mempunyai ciri fizikal lemah, glulam S3/D memperoleh rintangan tertinggi terhadap ubah bentuk elastik dan kepecahan, seperti yang ditunjukkan oleh penemuan daripada ujian lenturan statik dan pemampatan. S1/D pula mempunyai kekuatan ricih (2.89 N/mm^2) dan kekerasan yang paling tinggi (jejari: 1986.00 N, membujur: 2953.20 N). Analisis korelasi menunjukkan bahawa MOE (tepi) dan profil ketumpatan lamina S3/D mempunyai hubungan positif yang sangat kuat dan signifikan. Secara ringkasnya, rawatan VTC meningkatkan sifat fizikal lamina Paraserianthes falcataria sebanyak 49.16%, manakala sifat fizikal dan mekanikal glulam juga meningkat sebanyak 45.71% dan 50.08%. Rawatan tersebut juga telah mengurangkan keluasan sel lumen sebanyak 49.51%. Pengukusan selama 10 minit ialah durasi ideal untuk meningkatkan sifat fizikal lamina dan glulam, manakala pengukusan selama 30 minit telah meningkatkan sifat mekanikal glulam. Analisis korelasi menunjukkan bahawa peningkatan ketumpatan lamina meningkatkan kekuatan mekanikal glulam, yang mana pengukusan selama 30 minit menunjukkan hubungan positif yang signifikan.

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LIST OF ABBREVIATIONS

ANOVA	-	Analysis of Variance
ANSI	-	American National Standards Institute
ASTM	-	American Society for Testing and Materials
cm	-	Centimeter
cP	-	Centipoise
CR	-	Compression ratio
D	-	Density
DR	-	Delamination rate
e.g.	-	Exempli gratia
FESEM	-	Field Emission Scanning Electron Microscope
ft	-	Feet
g	-	Gram
JAS	-	Japanese Agricultural Standard
K	-	Constant Contact Angle Rate
kN	-	Kilo Newton
L	-	Longitudinal
LBDSA	-	Low Bond Axisymmetric Drop Shape Analysis
LSD	-	Least Significant Difference
MC	-	Moisture content
mm	-	Millimeter
mm/min	-	Millimeter per minute
MOE	-	Modulus of Elasticity
MOR	-	Modulus of Rupture
MPa	-	Megapascal
N	-	Newton
ND	-	Non-densified
NS	-	Non-pre-steamed
PRF	-	Phenol-Resorcinol Formaldehyde
PVAc	-	Polyvinyl Acetate
R	-	Radial

ROI	-	Region of Interest
s	-	Second
S/G	-	Shi & Gardner model
S1	-	Pre-steamed for 10 minutes
S2	-	Pre-steamed for 20 minutes
S3	-	Pre-steamed for 30 minutes
SEM	-	Scanning Electron Microscope
T	-	Tangential
TH	-	Thermo-Hydro
THM	-	Thermo-Hydro Mechanical
TS	-	Thickness Swelling
UTM	-	Universal Testing Machine
VTC	-	Viscoelastic-Thermal Compression
WA	-	Water Absorption

LIST OF SYMBOLS

%	-	Percentage
°	-	Degree
°C	-	Degree Celsius
±	-	Plus-Minus
Δ	-	Increment of test piece's neutral axis deflection, measured at midspan over distance and corresponding load
≤	-	Equal or less than
µL	-	Microliter
μm^2	-	Micrometer Square
A	-	Cross-section area
b	-	Width of test piece
$E_{c,0}$	-	Elastic modulus for compression parallel to grain
$E_{c,90}$	-	Elastic modulus for compression perpendicular to grain
F_2-F_1	-	Increment of load on straight line portion of load-deformation curve
F_{40}-F_{10}	-	Increment of load on straight line portion of load-deformation curve; F_{40} was 40% and F_{10} was 10% of $F_{c,90,max}$
$f_{c,0}$	-	Compressive strength for compression parallel to grain
F_{max}	-	Maximum load
g/m2	-	Gram per meter square
h	-	Depth of test piece
H_0	-	Gauge length
kN	-	Kilo Newton
l	-	Span length
l1	-	Maximum load
L_{tp}	-	Length of test piece
m^2	-	Meter square
mm^2	-	Millimeter square

n	-	Total number of test pieces
N/mm^2	-	Newton per milimeter square
no/mm^2	-	Number per milimeter square
P	-	Increment of load applied below proportional limit
P_{max}	-	Maximum load
R_{wf}	-	Wood failure
W_2-W_1	-	Increment of deformation corresponded to F_2-F_1
W_{40}-W_{10}	-	Increment of deformation corresponded to F_{40}-F_{10}

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Wood is widely known as an excellent material that possesses good properties such as good mechanical properties and excellent workability (Popescu *et al.,* 2014). Nowadays, big companies in the wood industry demand a more comprehensive range of utilizations of various wood species to reduce waste and enhance their competitiveness in domestic and global markets. In general, medium-heavy hardwood species exhibit better density than light hardwood species. However, denser wood species require a longer time to grow before being harvested, while low-density wood species often grow fast and can be harvested in a shorter time.

High-density wood species are often utilized for heavy-duty purposes, e.g., structural beams and trusses. In contrast, low-density wood species are commonly applied for light-medium duty purposes such as indoor furniture components. Low-density wood species are also frequently associated with good pulping characteristics, whereby they are further processed into paper (Cabi, no yr.). Low-density wood species can be densified by undergoing a densification process to enhance their mechanical strength, thus replacing high-density wood species to be utilized in the structural application (Hansmann *et al.,* 2005).