PHYSICO-MECHANICAL PROPERTIES OF CROSS-LAMINATED TIMBER MANUFACTURED FROM Acacia mangium WILLD. WOOD

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By

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December 2018

Chairman : Professor Paridah Md. Tahir, FASc
Institute : Tropical Forestry and Forest Products

Cross Laminated Timber (CLT) using mass timber has becoming more popular due to various sustainability advantages and benefits, notably the speed and ease with which CLT buildings can be constructed. This study evaluates the bond integrity and strength properties of CLT made from tropical *Acacia mangium* Willd. wood. In the preliminary study (Part 1), the bonding integrity of the CLT were assessed by determining the surface wettability using contact angle method, percent delamination and shear strength upon block shear test of CLT. The evaluation of bonding characteristics was done on two types of adhesive (PUR and PRF), three pressing pressures (0.9N/mm², 1.2 N/mm², 1.5N/mm²), and three adhesive spread rates (150g/m², 200g/m², 250g/m²). Two types of two-layer block shear samples were prepared with grain orientation parallel (denoted as parallel laminated block) and perpendicular (denoted as cross laminated block) to each other. The shear performance was conducted on two loading directions: parallel to end grain and perpendicular to the grain of the first layer. Additionally, delamination tests were performed on three-layer CLT to assess the durability of bonds in severe environmental conditions. Tests were conducted according to EN391 (Delamination test) and EN392 (Block shear test). The ANOVA in preliminary study shows that among the parameters studied (adhesive types, spread rate, pressing pressure and loading direction), only adhesive types have significant effect on both the extent of delamination and shear bond strength of the blocks. Whilst both adhesive spread rate and loading direction have a marked influence on the shear strength but not on percent delamination, irrespective of adhesive types. Loading direction appears to greatly influence the shear bond values and wood failure percentage. The effects was more pronounced in the parallel laminated block rather than cross laminated block. The results also revealed that PRF-bonded laminated block experienced lower percent delamination (50%) as compared to that bonded with one component PUR (80%). PRF was found to be a more superior adhesive than PUR irrespective of clamping pressure and loading direction. The superior performance of PRF can be attributed to strong chemical bonding, stable and

better gap-filling properties. Based on the optimum parameters in preliminary study, the larger sized (Part 2) were produced with (1000 (*l*) ×280 (*w*) ×54(*t*) mm), three-layer CLT were fabricated using *Acacia mangium* lumbers and its physical, mechanical and thermal properties were evaluated. Two types of adhesives were used: one-component polyurethane (PUR) and phenol resorcinol formaldehyde (PRF) as binders. Using a spread rate of 250g/m², the CLT was pressed at 1.5N/mm² for 1 hour 30 minutes. After conditioning, the CLT was tested according to European Standard, EN408 and prEN16351. Based on physical, mechanical and thermal properties, *Acacia mangium* can be converted to structural grade CLT provided that the maximum bending load is improved. CLT panels with PRF adhesive is more resistant in water compared to those bonded with PUR. The MOE and MOR of PRF-bonded CLT is superior than the PUR-bonded CLT higher in four- point bending, shear in bending and compression parallel to the grain. Different failure modes were observed in *Acacia mangium* CLT: rolling shear, glueline failure, tension, shearing and crushing. In thermal properties (thermogravimetric analysis and dynamic mechanical analysis), PRF imparts greater stability to *Acacia mangium* CLT compared to PUR.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SIFAT-SIFAT FISIKO-MEKANIKAL KAYU BERLAMINASI SILANG YANG DIPERBUAT DARIPADA KAYU *Acacia mangium* WILLD.

Oleh

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Kayu berlaminasi silang (CLT) menggunakan kayu bersaiz besar telah menjadi terkenal disebabkan kepelbagaian kelebihan dan faedah, terutamanya dari segi kepantasan dan kemudahan pemasangan pembinaan bangunan CLT. Kajian ini menilai sifat integriti dan kekuatan ikatan CLT daripada kayu tropika *Acacia mangium* Willd. Dalam kajian pertama (Bahagian 1), sifat ikatan integriti CLT dinilai dengan menentukan kelembapan permukaan kayu menggunakan kaedah sudut sentuhan, peratus delaminasi dan kekuatan ricih melalui geseran blok CLT. Penilaian terhadap sifat integriti dan kekuatan ikatan CLT menggunakan dua jenis perekat iaitu (PRF dan PUR), tiga jenis tekanan untuk menekan (0.9N / mm², 1.2 N / mm², 1.5N / mm²), dan tiga jenis kadar sebaran perekat (150g / m², 200g / m², 250g / m²). Terdapat dua jenis sampel blok ricih dua lapisan telah dihasilkan iaitu orientasi selari (dilabelkan sebagai blok berlamina selari) dan orientasi berserenjang (dilabelkan sebagai blok berlaminasi silang) antara satu sama lain. Ujian ricih dilakukan pada dua arah pemuatan iaitu selari dan berserenjang. Di samping itu, ujian delaminasi telah dilakukan pada tiga lapisan CLT untuk menilai tahap ketahanan ikatan perekat dan kayu dalam keadaan alam sekitar yang berbeza. Ujian dilakukan mengikut piawaian EN 391 (ujian delaminasi) dan EN392 (ujian blok geseran). Pengujian analisis daripada variasi (ANOVA) menunjukkan bahawa hanya jenis perekat yang mempunyai kesan signifikasi terhadap delaminasi dan kekuatan ikatan blok ricih berbanding parameter yang lain (kadar penyebaran perekat, tekanan menekan dan arah muatan). Kadar sebaran perekat dan arah pemuatan mempunyai kesan yang ketara pada kekuatan blok ricih tetapi tidak pada peratus delaminasi, tanpa mengira jenis perekat yang digunakan. Manakala arah beban juga mempengaruhi nilai ikatan ricih dan peratus kegagalan kayu. Kesannya lebih ketara dalam blok berlamina selari berbanding blok berlamina silang. Didalam pengujian peratus delaminasi kayu, blok berlamina PRF lebih rendah berbanding blok berlamina PUR dengan peratus 50% dan 80%. PRF merupakn perekat yang lebih bagus berbanding perekat PUR tanpa mengira tahap tekanan menekan dan arah pemuatan. Prestasi perekat PRF dapat dikaitkn dengan ikatan kimia

yang kuat, stabil dan lebih baik dalam pengisian jurang berbanding PUR. Berdasarkan optimum parameter daripada kajian awal, ukuran sampel yang lebih besar (Bahagian 2) telah dihasilkan dengan saiz berukuran (1000 (l) × 280 (w) × 54 (t) mm), tiga lapisan CLT telah dibuat menggunakan kayu *Acacia mangium* dan sifat fizikal, ,mekanikal dan termal dinilai. Dua jenis perekat digunakan: satu komponen poliuretana (PUR) dan phenol resorcinol formaldehyde (PRF) sebagai pengikat di antara kayu dan perekat. Kadar penyebaran 250g/m², dan tekanan menekan CLT pada 1.5N/mm² selama 1 jam 30 minit. Selepas pengkondisian, sampel CLT telah diuji mengikut piawaian Eropah iaitu EN 408 dan prEN16351. Berdasarkan sifat fizikal, mekanikal dan termal, kayu *Acacia mangium* boleh menjadi salah satu gred kayu untuk struktur CLT dengan syarat memperbaiki tahap beban lenturan yang maksimum. Manakala, panel CLT daripada perekat PRF menghasilkan rintangan air dan prestasi yang lebih baik berbanding perekat PUR. Begitu juga, MOE dan MOR bagi CLT daripada perekat PRF lebih bagus berbanding CLT daripada perekat PUR di dalam pengujian mekanikal. Perbezaan kegagalan mod bagi CLT daripada *Acacia mangium*: *rolling shear, glueline failure, tension, shearing and crushing*. Didalam sifat thermal (analisa thermogravimetrik dan analisis mekanikal dinamik), perekat PRF menunjukkan kestabilan yang lebih besar kepada *Acacia mangium* CLT berbanding perekat PUR.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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This is to confirm that

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LIST OF ABBREVIATIONS

º	Degree
ºC	Degree celsius
ºF	degree Celsius in Fahrenheit
%	Percentage
ANOVA	Analysis of variance
CLT	Cross laminated timber
CO_2	Carbon dioxide
df	Degree of freedom
EPI	Emulsion polymer isocyanate
g	gram
g/m²	gram per square meter
GLULAM	Glued-laminated timber
Kg/m³	kilogram per cubic meter
KPa	Kilopascal
l	Length
LSD	Least significance different
LVL	Laminated veneer lumber
m	Meter
M_1	Mass
MC	Moisture content
MDF	Medium density fibreboard
MF	Melamine formaldehyde
mm	Millimeter
MOE	Modulus of elasticity
MOR	Modulus of rupture
MPa	Megapascal
MUF	Melamine-urea-formaldehyde
N/mm²	Newton per square millimeter
pH	Potential of hydrogen
PRF	Phenol resorcinol formaldehyde
Psi	Pounds per square inch
PUR	One component polyurethane
R^2	R- squared
RF	Radio frequency
RH	Relative humidity
SG	Specific gravity
t	Thickness
TS	Thickness swelling
V	Volume
w	Width
WA	Water absorption

1.5 Organization of The Chapters

This thesis is organized into five chapters. The first chapter gives a general overview of Cross Laminated Timber (CLT) and *Acacia mangium* wood, problem statement, justification, and objectives of this study. The second chapter reviews on the relevant literature associated to the topic, which includes the Cross Laminated Timber (CLT), *Acacia mangium*, adhesives used in CLT, manufacturing parameters, performance of CLT, and applications of CLT.

The third chapter focuses on the preliminary study and basic properties by determination of the bonding properties of *Acacia mangium* through the moisture content, density, surface wettability by contact angle, percent of delamination and shear bond strength as affected by different adhesive types, pressing pressure (0.9 N/mm^2, 1.2 N/mm^2, 1.5 N/mm^2) and adhesive spread rate (150 g/m^2, 200 g/m^2, 250 g/m^2) on the contact angle, block shear strength with four different loading direction and delamination test.

Based on the optimum results of adhesive spread rate (250 g/m^2) and pressing pressure (1.5 N/mm^2) from the chapter three it were undergo to the chapter four. This chapter (Chapter four) were discusses the properties of CLT manufactured from *Acacia mangium* wood bonded using different types of adhesives which is one component polyurethane (PUR) and phenol resorcinol formaldehyde (PRF). The results were then compared to adhesives (PUR and PRF) in physical, mechanical and thermal properties. The final chapter (Chapter 5) summarizes the whole thesis and gives a conclusion and some recommendations for future work.

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