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SUITABILITY OF ASPEN (*POPULUS TREMULA* L.) FOR CROSS-LAMINATED TIMBER (CLT)

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ABSTRACT

Cross-laminated timber (CLT) CLT is an excellent material for building and high load-bearing structural applications, but its fabrication and use are limited to softwood only. The suitability of aspen (*Populus tremula* L) wood for manufacturing CLT was assessed by using two adhesives, one-component polyurethane (1C-PUR) and melamine adhesive (ME). Physical properties like water absorption (WA), thickness swelling (TS), delamination, and mechanical properties like bond shear strength, bending modulus of elasticity, bending strength, and rolling shear strength were evaluated to examine its suitability. Compared to ME-bonded CLT, 1C-PUR bonded CLT panels displayed superior physical characteristics, with 70% passing the delamination test. CLT panels bonded with 1C-PUR adhesive also have better mechanical properties than ME-bonded CLT. CLT panels experienced three types of bending failure: rolling shear, delamination, and tension. Aspen CLT has similar or higher mechanical properties than traditional softwoods, making it suitable for CLT manufacturing.

KEYWORDS: Aspen, cross-laminated timber, physical properties, mechanical properties.

INTRODUCTION

The demand for wood-based materials is constantly increasing with the growing population (Srivaro et al. 2019). With the growing demand for wood-based materials and declining natural forest stands, lower-grade hardwoods and plantation timber species have emerged as sustainable alternatives (Lu et al. 2018). Cross Laminated Timber (CLT), an advanced engineered wood material mainly used for structural applications, was developed in Europe in the early 1990s (Brandner et al. 2016). Because of its sustainability and specific strength, CLT emerged as a potential replacement for traditional building materials such as concrete and steel (Brandner et al. 2016). The annual global output of CLT is expected to increase to 3,000,000 m^3 by 2025 from 50,000 m^3 in 2000 and 625,000 m^3 in 2014 (Liang et al. 2022). A typical CLT panel comprises three or more odd layers joined orthogonally with a structural adhesive. Softwood species such as European spruce, Scot pine and Douglas fir, known as SPF (spruce-pine-fir), are primary species used to make CLT panels (Dong et al. 2023). The decline in the natural forest cover and increasing demand for mass timber products has prompted several studies (Srivaro et al. 2019, Mohd Yusof et al. 2019, Liew and Maining 2021, Musah et al. 2021, Das et al. 2023) to examine the viability of employing hardwood or fast-growing wood species to examine their suitability for CLT manufacturing.

Aspen (*Populus tremula* L.) is a fast-growing, economically feasible with excellent sawmilling capabilities, and has the essential mechanical qualities needed for CLT for structural load carrying, which is why the idea of creating CLT panels from this material first emerged (Brandner et al. 2016). Traditional uses of aspen timber include the production of pulp, particleboard, solid wood, and other goods (e.g., pencils, skis, sauna benches and coffins). It has not attracted the attention it deserves for structural applications due to its low strength, moderate stiffness, and high shrinkage. Like other hardwoods, aspen has not always been considered as a construction material. However, including poplar with fifteen other softwood species for CLT manufacturing in the recent version of the European standard for CLT will encourage the manufacturers to prioritize its use in structural applications. Recently, many researchers have studied the suitability of poplar species for both homogenous and hybrid CLT panels by analyzing their mechanical and bonding properties. Rostampour et al. (2022) examined the bending and shear strengths of CLT produced from poplar (*Populus alba*) both in major and minor axis orientations and observed that the 0/30/0 arrangement provides the optimum strength in both directions. Kramer et al. (2014) examined the bending strength of hybrid poplar (*Pacific albus*) CLTs in a different study and found that the CLTs met the shear and bending performance for Grade E3 of ANSI/APA PRG-320 (2019) but did not fulfill the requirement for bending stiffness. Similarly, Vetsch (2015) observed a lower modulus of elasticity (8068 N/mm^2) and modulus of rupture (13.26 N/mm^2) in aspen (*Populus tremula* L.) CLT bonded with polyvinyl acetate (PVAc) adhesive which was below the standard requirement. Moreover, complete delamination failure was also observed. Wang et al. (2014) discovered that poplar (*Populus euramericana*) might be utilized as a transverse layer for CLT panels with face layers of Douglas fir (*Pseudotsuga menziesii*) and Monterey pine (*Pinus radiata* D. Don) with similar strength to pure Douglas fir CLT.

Many researchers are primarily focused on mechanical strength and bonding properties of hardwood CLTs. However, no relevant information is available concerning the physical properties like water absorption (WA) and thickness swelling (TS). Swelling and shrinkage are crucial considerations in constructing CLT structures, as they are primarily hygroscopic wood. Wood will shrink and expand with changes in the relative humidity of the atmosphere, which would impact the stability of the building structure. Due to its orthogonal layer arrangement, CLT has a significantly different dimensional swelling and shrinkage coefficient in all three directions (radial, tangential, and longitudinal) than solid wood or glulam (Gereke and Niemz 2010). It was also reported that the dimensional expansion coefficient of CLT is three times higher than that of solid wood or glulam in the length direction and slightly higher than that of solid wood or glulam along thickness (Liang et al. 2022). The TS of CLT can be impacted by the type of wood used, lamination thickness, and adhesive used (Liang et al. 2022). According to Mohd Yusof et al. (2019), adhesive substantially impacted the mean TS of *Acacia mangium* CLT manufactured with phenol resorcinol formaldehyde (PRF) and polyurethane (PUR) adhesives, which were 1.053% and 0.696%, respectively. In another research, Srivaro et al. (2019) reported that only the compressive shear strength of oil palm (*Elaeis guineensis* Jacq) CLT meet the required standard value. They further noted that increasing the bonding pressure could reduce the thickness swelling (*TS*) and water absorption (WA). Liew and Maining (2021) examined the mechanical and physical characteristics of CLT panels manufactured from Batai (*Paraserianthes falcataria*) using PRF adhesive with various glue spreads (150, 200, 250 and 300 g/m^2) and reported that higher glue spread of 300 g/m^2 resulted in improved physical and mechanical properties. Srivaro et al. (2021) found that resin content and clamping pressure had no significant effect on the physical and mechanical properties of rubberwood (*Hevea brasiliensis*) CLTs; however, the mechanical properties were due to its higher density than softwood CLTs. Gereke and Niemz (2010) reported that the maximum stresses developed along the glueline due to the tangential and radial shrinkage variation. They further noted that the annual ring angle, middle layer characteristics, and layer thickness ratios considerably impact panel deformation (warpage) and induced stresses. Therefore, it is always essential to examine the physical properties like WA and TS for the durability and stability of CLT panels. These earlier researches support the hypothesis for this study, that the aspen can be a suitable material for CLT manufacturing with respect to its physical and mechanical properties.

This study aims to investigate the suitability of aspen wood for CLT and ascertain the physical and mechanical properties of aspen CLT. A comparative analysis was also carried out with published results from softwood CLTs of similar density to examine the performance of aspen CLT.

MATERIAL AND METHODS

CLT preparation

Fast-grown aspen lumbers were purchased from a supplier in the Czech Republic. The average was 385 kg/m^3. The physical and mechanical properties of aspen wood are shown in Tab. 1. The lumbers were conditioned for six weeks at 20°C and 65% relative humidity and then sawn, trimmed and planed into 2200 mm long, 75 mm wide and 20 mm thick lamellas. Before CLT manufacturing, the lamellas were graded visually according to EN 14081+A1 (2016) to select the outer and core lamellas. CLT panels were prepared by using two commercially available adhesives: liquid melamine adhesive (ME) (AkzoNobel, Netherland), formulated by combining liquid melamine glue (Plus A011) with hardener (H011,) and one component polyurethane (1C-PUR) adhesive (Adhesive 2010) (AkzoNobel, Netherland). The properties of the adhesives are enlisted in Tab. 2. Both the adhesives were applied on one side of the face lamellas with the help of a spatula. No edge gluing was done during the whole manufacturing process. This is because the benefits of edge gluing have been reported to be negligible when considering swelling and shrinkage (Brandner et al. 2016). The glue spread was 250 g/m^2 and 160 g/m^2 for ME and 1C-PUR adhesive, respectively. For ME, the adhesive and hardener mixing ratio was 70:30 by weight. The glued panels were assembled and then pressed for 1 hour at 20°C in a hydraulic press with a specific pressure of 0.6 N/mm^2. Then panels were conditioned for three weeks at 65 ± 5 % RH and 20 °C before being cut into specimens for testing. A total of 20 CLT panels were prepared in this study.

Tab. 1: Properties of aspen wood.

Specific gravity	**Swelling** (%)			**Shrinkage** (%)			**Modulus of Elasticity** (N/mm^2)
	radial	**tangential**	**volumetric**	**radial**	**tangential**	**volumetric**	
0.38	3.9	9.6	14.1	3.5	6.7	11.5	8100

Tab. 2: Properties of the adhesives.

Properties	**Polyurethane (1C-PUR) (Adhesive 2010)**	**Melamine (ME) adhesive**	
		Melamine Adhesive (A011)	**Hardener (H011)**
Color	White	Opaque white	White
Viscosity (mPas)	6000 – 19000	1500 – 9000	1700 – 2700
Solid content (%)	100	65	–
Density (kg/m^3)	1160	1290	1070

Experimental testing of the samples

Water absorption & thickness swelling

Both water absorption (WA) and thickness swelling (TS) of the CLT panels were performed on the same specimen, according to research of the Mohd Yusof et al. (2019). Twelve specimens of 70 × 70 × 60 mm^3 (l × b × t) were prepared from each CLT type. The moisture content of each specimen before testing was approximately 12%. The specimens were weighed and measured before being immersed in distilled water at normal room temperature (20°C). After 2 hours of immersion, the specimens were removed and dried, and their weight and thickness were recorded. After measurement, the specimens were again immersed in distilled water for 24 hours. Then the specimens were removed and dried again. The final weight and dimensions were measured. From the data obtained, the percentage of water absorption and thickness swelling was calculated using the following Eq. 1 and Eq. 2:

$$WA\ (\%) = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

$$TS\ (\%) = \frac{T_2 - T_1}{T_1} \times 100 \quad (2)$$

where: W_1 is the initial weight of specimens before immersion (g), W_2 is the final weight of specimens after 2 h and 24 h immersion (g), T_1 is the initial thickness of specimens before immersion (mm) and T_2 is the final thickness of specimens after 2 h and 24 h immersion (mm).

Delamination

The specimens for the delamination test were taken by making a quadratic cut from the CLT panels. The dimension of the specimens was $100 \times 100 \times 60$ mm^3. For each adhesive type, ten specimens were tested according to EN 16351 (2015). The specimens were weighed first and then placed in a pressure vessel. Water was added to the pressure vessels at an ambient temperature (20°C) until the specimens got submerged. Then a vacuum of 70 kPa was drawn and held for 30 min. Subsequently, the vacuum was released, and a pressure of 550 kPa was applied for 2 h. The pressure was then released, and specimens were dried for 15 hours in a circulating oven at 70 ± 5°C. Delamination was recorded in the specimens when their mass was 100 – 110% of their original mass. The delamination of the glue lines was observed upon removal from the oven. The length of the delamination was recorded between the two delaminated surfaces. Measurements were recorded only when the delamination depth was less than 2.5 mm and more than 5 mm from the nearest delamination. The following Eq. 3 and 4 were used for calculation of the total delamination and maximum delamination:

$$D_{tot}(\%) = \frac{L_{tot.delam}}{L_{tot.glueline}} \times 100 \quad (3)$$

$$D_{max}(\%) = \frac{L_{max.delam}}{L_{glueline}} \times 100 \quad (4)$$

where: D_{tot} is the total delamination (%), D_{max} is the maximum delamination (%), $L_{tot.delam}$ is the total delamination length (mm), $L_{tot.glueline}$ is the sum of the perimeter of all glue lines in specimens (mm), $L_{max.delam}$ is the maximum delamination length (mm) and $L_{glueline}$ is the perimeter of one glue line in a delamination specimen (mm).

Following the delamination assessment, all bonds were split with a hammer and chisel to evaluate the surfaces of the split glued areas for wood failure (*WF*). The *WF* (%) was visually estimated for each specimen. Defective wood areas were excluded from the evaluation and deducted from the overall bonding surface.

Bond shear

The bond shear test was carried out by a double shear test method as suggested by Das et al. (2022) with compression loading (Fig. 1), with a shear area of 40×40 mm^2.

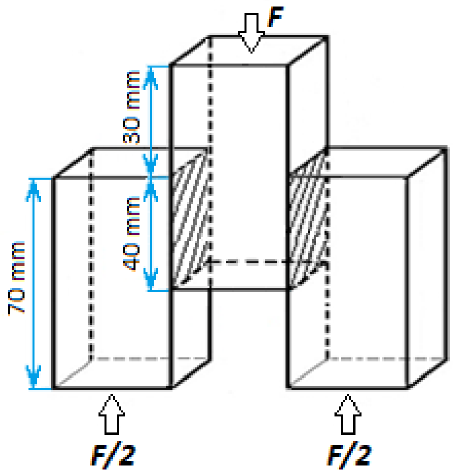

Fig. 1: Schematic diagram of the shear specimen.

A total of 10 specimens were evaluated for each adhesive type. The specimens were conditioned at 20°C and 65 % relative humidity until they reached a constant weight. The shear test was performed using a universal testing machine (UTS 50, TIRA, Germany). The load was applied at a pace that caused failure within 30 to 90 seconds. The shear strength was calculated using Eq. 5:

$$f_v = \frac{F_u}{2 \times A} \qquad (5)$$

where: f_v is the shear strength (N/mm^2), F_u is the ultimate load (N) and A is the total sheared area (40 × 40) (mm^2).

Bending and rolling shear test

Four-point bending test was performed to examine the bending and rolling shear strength of CLT panels according to EN 16351 (2015). The test was carried out using a universal testing machine (TIRA 2850 S E5, Germany) following the procedure as laid out in EN 408 (2010). A span of 18 times the thickness of the CLT panel (l = 2a + 6h) was used to evaluate bending strength and stiffness. In comparison, 9 times the thickness of the CLT panel (l = 2a + 3h) was used to assess rolling shear strength, as shown in the figure (Fig. 2). The CLT panels were supported over the two supports. The distance between the load points was equivalent to six and three times the depth of the CLT panels for bending and rolling shear tests, respectively. The load was applied steadily until it reached its maximum in 300 ± 120 seconds. The computer directly connected to the testing apparatus recorded the maximum loading force and deflection.

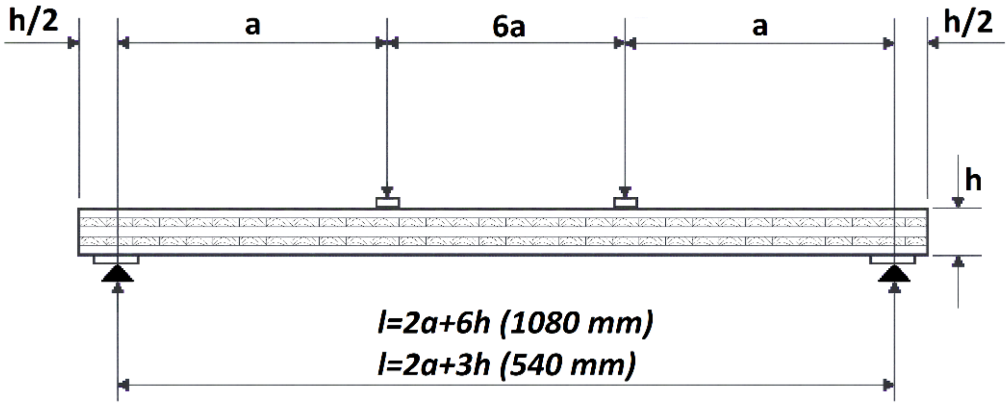

Fig. 2: Schematic diagram of bending test (a = 6h) and rolling shear test (a = 3h).

The global bending modulus of elasticity (E_{mg}) was calculated using Eq. 6 according to EN 408 (2010):

$$E_{mg} = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{W_2 - W_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \quad (6)$$

where: E_{mg} is the global bending modulus of elasticity (N/mm^2), a is the distance between a loading position and the nearest support during the bending test (mm), l is the length of the beam between supports (mm), b and h are the width and height of the specimens (mm), $F_2 - F_1$ is the increment of load (N), $W_2 - W_1$ is the increment of displacement corresponding to $F_2 - F_1$ (mm) and G is the shear modulus = 650 (N/mm^2).

The bending strength (f_m) of the individual test piece was also calculated according to EN 408 (2010) using the Eq. 7:

$$f_m = \frac{3Fa}{bh^2} \quad (7)$$

where: f_m is the bending strength (N/mm^2), F is the maximum load (N), a is the distance between the load and the nearest support during the bending test (mm), b and h are the width and height of the specimens (mm), respectively.

Rolling shear strength (f_r) was calculated using Eq. 8:

$$f_r = \frac{3F_u}{4bh} \quad (8)$$

where: f_r is the rolling shear strength (N/mm^2), F_u is the maximum load (N), b and h are the width and height of the specimens (mm), respectively.

Statistical analysis

One-way analysis of variance (ANOVA) was performed with Statistica 13 (TIBCO Software Inc., USA) to study the effect of adhesive type on the physical and mechanical properties of CLT. These effects were investigated using the least significant difference (LSD) method.

RESULTS AND DISCUSSION

Physical properties of aspen CLT

Tab. 3 shows statistical results for physical (*WA*, *TS*) and delamination properties of both 1C-PUR and ME bonded aspen CLT panels.

Tab. 3: Physical properties of CLT with both types of adhesives.

Panel Type	***WA 2h***	***TS 2h***	***WA 24h***	***TS 24h***	D_{tot}	D_{max}	***WF***
1C- PUR							
Max	39.35	5.65	61.54	8.58	65.98	52.54	100
Min	29.17	2.07	47.78	3.43	0.00	0.00	0.00
Mean	33.052^{A}	2.883^{A}	55.099^{A}	4.933^{A}	13.694^{A}	26.113^{A}	83.676^{A}
ME							
Max	39.74	5.87	68.78	9.65	86.51	78.14	100
Min	29.31	2.09	48.85	3.92	0.00	0.00	0.00
Mean	34.687^{A}	4.136^{B}	59.859^{A}	7.299^{B}	33.452^{B}	45.609^{B}	66.195^{B}

Means followed by different letters (A, B) are statistically insignificant at $p \leq 0.05$ according to LSD.

Fig. 3 shows the *WA* and *TS* properties of 1C-PUR and ME glued aspen CLT specimens after 2 hours and 24 hours of soaking. Statistical analysis revealed a significant effect of adhesive type on both *WA* and *TS*.

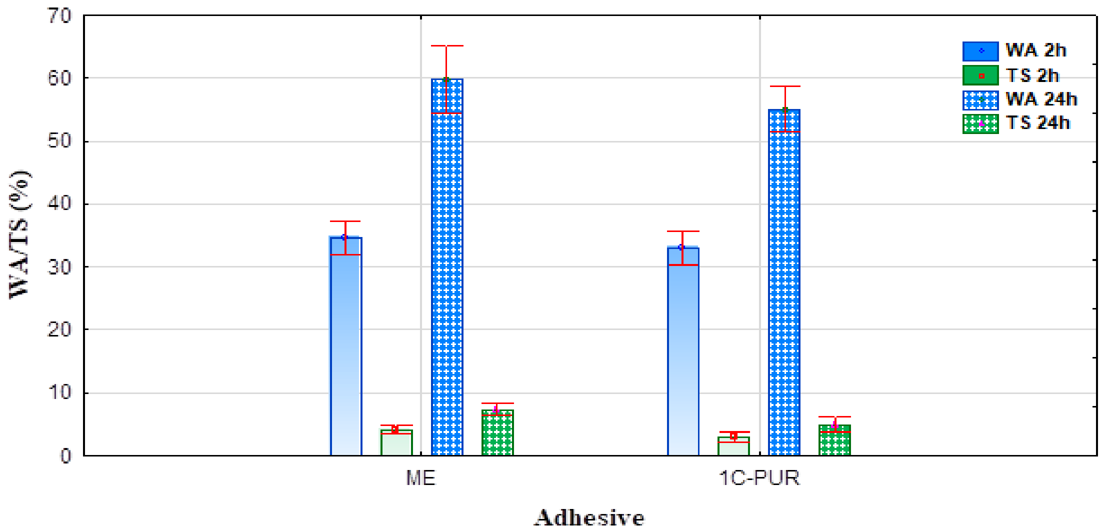

Fig. 3: Water absorption and thickness swelling of CLT panels.

1C-PUR bonded CLT specimens are more water resistant than ME bonded ones, as reflected by the lower values of *WA* and *TS*. A significant rise in the *WA* value was seen in the first 2 hours of the test, increasing by 34% for both adhesive types. This may be related to the aspen's excellent permeability as a diffused porous wood (Ross 2010). Further submersion of the samples beyond 2 h to 24 h caused only a gradual increase in the water uptake. The *TS* value after 2 h test was 4.1 %, which increased to 7.3% after 24 h immersion for ME-bonded CLT panels. With a TS of 4.9% and a *WA* of about 55% following 24h submersion, panels bonded with 1C-PUR are significantly more stable than panels bonded with ME adhesive. Similar results for *WA* and *TS* in for laminated veneer lumber (LVL) made of aspen wood have been reported by Shukla and Kamdem (2008). Further, aspen wood reportedly has higher swelling and shrinkage coefficients attributed to higher water penetration (Ross 2010). When the cross-section or end grain is exposed to water, absorption occurs more quickly along the length (Ross 2010). Due to the cross-lamination feature, absorption happens more rapidly when the cross-section or end grain is exposed to water (Ross 2010). The non-edge gluing of the lamellae also increases the surface area for more moisture absorption (Sikora et al. 2016a). Due to its orthogonal arrangement, the CLT panel is also more prone to thickness swelling and shrinking (Srivaro et al. 2019). According to Wimmer et al. (2013), 1C-PUR adhesives are more resistant to water absorption and swelling than PVA, MF, and PRF adhesives.

The results of the total delamination (D_{tot}), maximum delamination (D_{max}) and wood failure (*WF*) are shown in Fig. 4. These parameters were also significantly affected by the adhesive types. For 1C-PUR bonded specimens, the average *WF* was 83.7%, and the average D_{tot} was 13.7%, whereas for ME bonded CLTs, the average *WF* was 66.2%, and the average D_{tot} was 33.4%. A qualitative analysis was performed to present the delamination test results according to the minimum requirement in EN 16351 (2015).

The specimens bonded with 1C-PUR adhesives performed better, with 70% passing the delamination requirement in this study. However, the performance of CLT bonded with ME was miserable, with an 80% failure rate. This might be due to the enhanced gap-filling abilities of 1C-PUR adhesive. Several previous studies observed similar results. According to Konnerth et al. (2016), poplar glulam glued with Melamine Urea Formaldehyde (MUF) and 1C-PUR did not meet the minimum value specified in the standard; however, the mean delamination was 17.35% for MUF-bonded glulam and 9.9% for 1C-PUR bonded glulam.

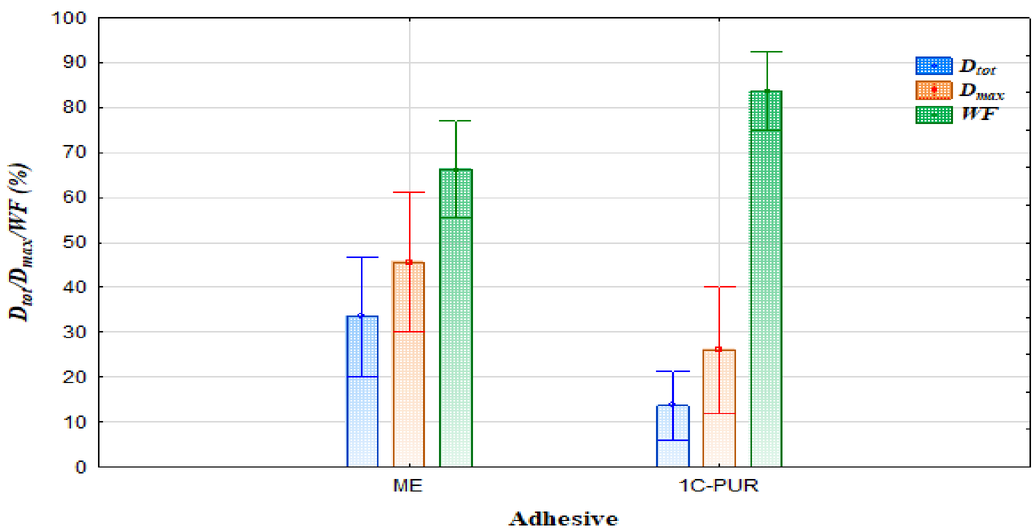

Fig. 4: Total (D_{tot}) delamination, maximum delamination (D_{max}) and wood failure (WF) of the CLT.

Similarly, Musah et al. (2021) reported increased delamination for aspen CLTs bonded using melamine adhesive (MF), with 50% of specimens failing during the delamination test. Melamine-based adhesives require longer closed assembly times and higher hardener contents for adequate bonding (Konnerth et al. 2016, Frihart and Hunt 2010), but as we have limited the closed assembly time to the manufacturer's suggested 1 hour with a 30% hardener content may result in poor bonding. It was further reported that the glueline thickness and strength are influenced by adhesive penetration, resultant of adhesive viscosity (Musah et al. 2021), with less viscous ME (1500–9000 mPas) entering deeply into cell lumina and resulting in starved joints. Further, Frihart and Hunt (2010) reported that solvents used in stiff structural adhesives like melamine-formaldehyde (MF) could cause voids in the glue, resulting in poor bonding during the curing process. Also, delamination was more pronounced in wood species with higher swelling coefficients than those with lower swelling coefficients (Konnerth et al. 2016). Aspen wood possessed a higher swelling coefficient, as high as 9.6 % in the tangential direction and 3.9 % in the radial direction (Ross 2010), which resulted in delamination more likely to occur, particularly on the tangential side. Moreover, the edge gaps between lamellas also allowed more water to penetrate the wood through the edges resulting in delamination (Sikora et al. 2016a). In a nutshell, 1C-PUR bonded panels displayed better bonding (with higher *WF* and lower D_{tot}) than ME bonding.

Mechanical properties of Aspen CLT

The mechanical properties of aspen CLT are summarized in Table 4. The findings suggest that 1C-PUR performed better in comparison to ME. In a similar study, Mohd Yusof et al. (2019) observed better mechanical properties in PRF-bonded wood of *Acacia mangium* CLT than in PUR-bonded CLT, irrespective of the similar density panels.

Tab. 4: Mechanical properties of CLT with both types of adhesives.

Adhesive	Bond shear	Bending properties		
	f_v	E_{mg}	f_m	f_r
1C- PUR	3.245^{A} (3.00 – 3.41)	8183.8^{A} (7617.99 – 8936.90)	31.290^{A} (27.09 – 33.63)	2.005^{A} (1.84 – 2.21)
ME	2.799^{B} (2.44 – 3.24)	7907.3^{A} (7490.28 – 8303.20)	30.350^{A} (26.18 – 33.25)	1.887^{A} (1.62 – 2.20)

Means followed by different letters (A, B) are only statistically significant at p ≤ 0.05, according to LSD. Values in parentheses represent the minimum and maximum values.

Bond shear strength

The average bond shear strength of aspen CLT bonded with 1C-PUR and ME are shown in Fig. 5.

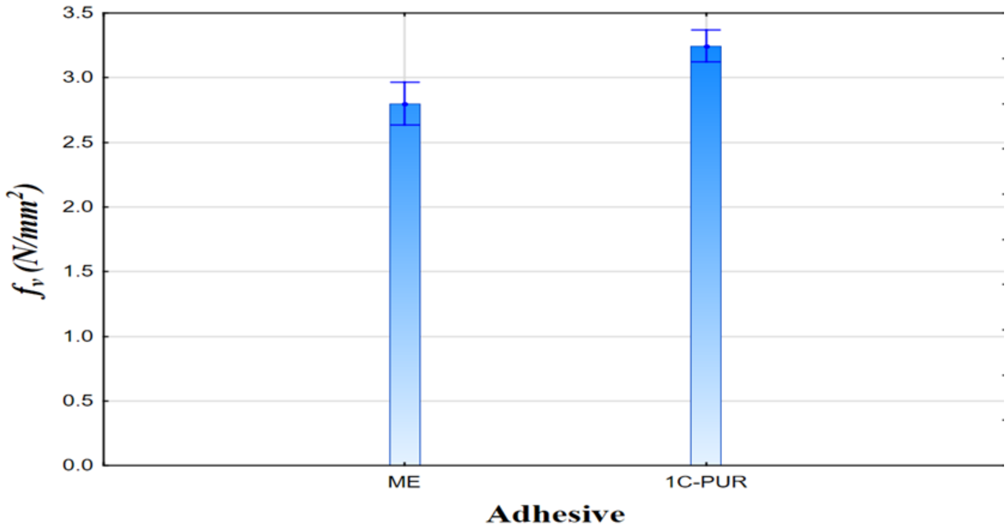

Fig. 5: Shear strength (f_v) of the CLT specimens.

The mean shear strength of aspen CLT bonded with 1C-PUR was 3.2 N/mm^{2,} while that bonded with ME was 2.8 N/mm^2. The shear strength of 1C-PUR bonding was significantly higher than ME bonding (*p-value = 0.001*). During the double shear test under compression loading, the glueline at the fixed end of the CLT panel failed due to maximum shear stress. Das et al. (2023) observed similar results. They further reported that, the double shear test method accurately predicted the shear strength with a 5–10% variation from the actual shear strength. The double shear test method minimized the effect of the rolling shear of CLT and exhibited a superior homogeneity of shear stress distribution, resulting in higher wood failure. It was also observed that the double shear test method reduced the impact of CLT's rolling shear and demonstrated better homogeneity of shear stress distribution, which increased wood failure (70%) in most of the specimen (Gao et al. 2022). Further, aspen, a lower-density timber, has a smaller contact angle and excellent wettability, speeding up the adhesive's absorption and boosting the shear strength (Oberhofnerová and Pánek 2016). Similarly, Lu et al. (2018) reported higher shear strength of 3.51 N/mm^2 in *Eucalyptus* CLT bonded with PUR adhesive compared to other adhesives like EP, EPI and PRF. Despite the significant variation in the experimental data for both adhesives, all the CLT specimens met the minimum required value (1 N/mm^2) as per annex D of EN 16351 (2015).

Bending strength and Modulus of elasticity

The global bending modulus of elasticity (E_{mg}) and bending strength (f_m) of aspen CLTs bonded with 1C-PUR and ME are shown in Fig. 6.

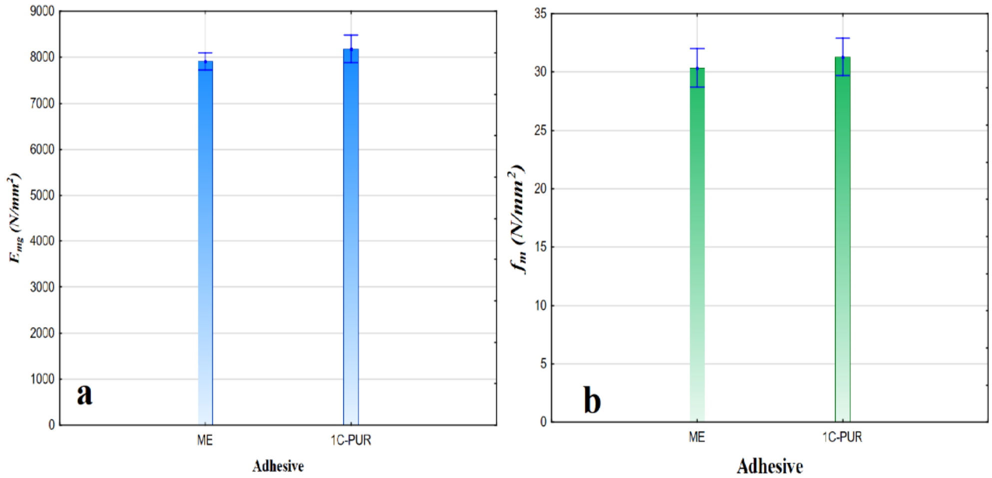

Fig. 6: Global bending modulus of elasticity (E_{mg}) [a] and bending strength (f_m) [b] of the CLT.

The E_{mg} of 1C-PUR bonded CLT panels was 8183 N/mm^2, marginally higher than the ME bonded CLT (7907 N/mm^2) without any significant difference (*p-value =0.092*). Similarly, the average bending strengths (f_m) of 1C-PUR and ME bonded CLT were 31.29 N/mm^2 and 30.35 N/mm^2, respectively, and again the difference was within experimental error. The results suggest that bending properties such as bending strength and bending stiffness are least affected by the adhesive types used in the study. Mohd Yusof et al. (2019) observed similar results. Furthermore, it was reported that the bending properties of CLT panels are determined by the strength of the core and bottom lamellas used in manufacturing the panels (He et al. 2018). Although the variation of 1C-PUR bonded CLT panels is significantly higher than that of ME bonded panels (6.84%), the average bending strength (f_m)of the 1C-PUR bonded CLT panels was higher than that of the ME bonded CLT panel by 2.6%, indicating that 1C-PUR may provide a better bending strength in CLT panels than ME adhesive. Additionally, it was noted that the mean global bending modulus of elasticity (E_{mg}) obtained in our study is approximately 7.5% higher than that obtained by Kramer et al. (2014) and 10% higher than that obtained by Vetsch (2015). Similarly, the mean bending strength (f_m) in our study is approximately 15.5% and 140% higher in both cases. In a study, Buck et al. (2016) noted that the global bending modulus of elasticity (E_{mg}) varied from 7601 to 8971 N/mm^2 and the bending strength (f_m) ranged from 29.1 to 38.4 N/mm^2 in CLT panels made of Norway spruce (*Picea abies* (L.) H. Karst.), a pioneer species that is commonly used to make CLT. Consequently, the findings indicated that aspen, a low-density plantation wood, might be able to meet the bending strength requirements of CLT.

Rolling shear strength

The results pertaining to the rolling shear strength (f_r) of CLT panels are shown in Fig. 7. The f_r of aspen CLT bonded with ME ranged from 1.73 N/mm^2 to 2.04 N/mm^2 with a mean value of 1.88 N/mm^2 whereas that bonded with 1C-PUR was between 1.91 N/mm^2 to 2.1 N/mm^2 with a mean value of 2.0 N/mm^2.

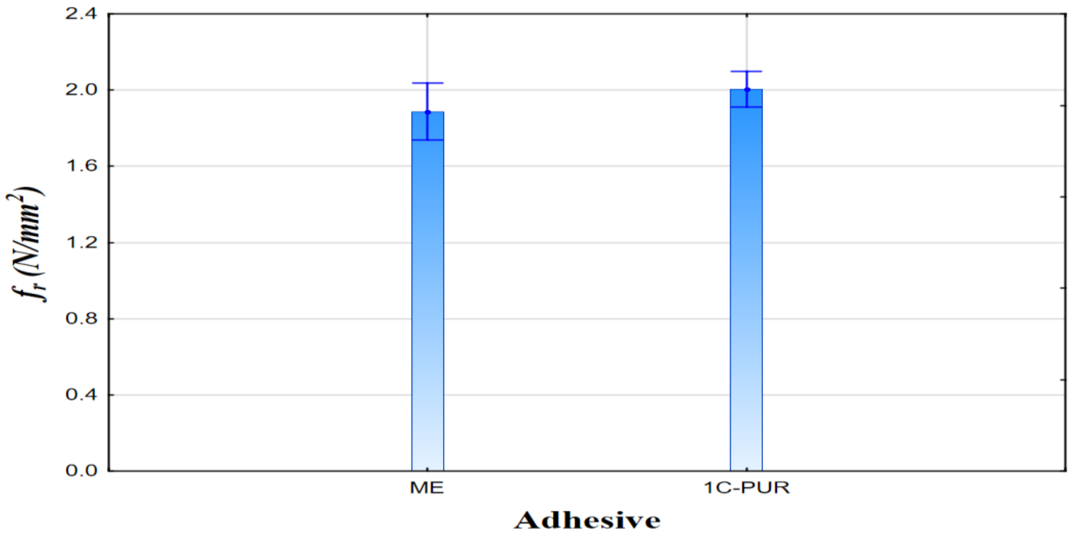

Fig. 7: Rolling shear strength (f_r) of CLT panels.

The obtained test results are quite like those of earlier investigations. Gong et al. (2015) found the mean f_r of aspen (*Populus tremuloides*) is 2.88 N/mm^2. Statistical analysis reveals that the difference in the f_r values between the adhesive is insignificant (*p-value = 0.144*). The average f_r of 1C-PUR bonded CLT is 6.4 % higher than that of ME bonded CLT. A similar result was also reported by Sciomenta et al. (2021), who reported higher f_r (5.11 N/mm^2) in PUR-bonded beech CLT panels than the MUF-bonded beech CLT (4.24 N/mm^2). The characteristic rolling shear strength for SPF CLT is currently taken to be 0.6 N/mm^2 in Canada (ANSI/ APA PRG 320: 2019), while in Europe, the recommendation is for the characteristic rolling shear strength to be 1.1 N/mm^2 for both edge-glued and non-edge-glued softwood CLT with a minimum aspect ratio (w/t) $\geq$ 4, otherwise, 0.7 N/mm^2 should be used (EN 16351: 2015). As a result, the obtained result exceeds the requirements for softwood. These findings indicated that the fast-growing aspen wood has a lot of potential to be used as a building material in manufacturing CLT panels.

Failure modes

Delamination happens when a material experiences various stresses primarily due to swelling and shrinkage variability, resulting in drying defects like cupping, twisting, wrapping, checking, and honeycombing (Gereke and Niemz 2010). During the delamination test, it was observed that the gluelines lost their straight form, resulting in cupping, as shown in Fig. 8a, due to inherent factors such as wood pockets, tension wood, juvenile wood, or longitudinal stress. Further, the lamellas became susceptible to water penetration due to the lack of edge-gluing and rapid drying. As a result, water penetrates the lamellas ripping the wood fibers along the gluelines as illustrated in Fig. 8b, causing delamination. In the shear test method, it was observed that shear stress develops at the fixed end of the CLT panel, causing higher failure at the supports. About 70% of the failure was due to glueline failure at the supporting end (Fig. 8c), while 30% was due to a fracture in the core layer (Fig. 8d). This could be due to the orthogonal layout of the lamellas and the greater tension generated at the glueline with the increasing load. Similarly, Gao et al. (2022) found that most glulam specimens failed at the glueline at the supporting end.

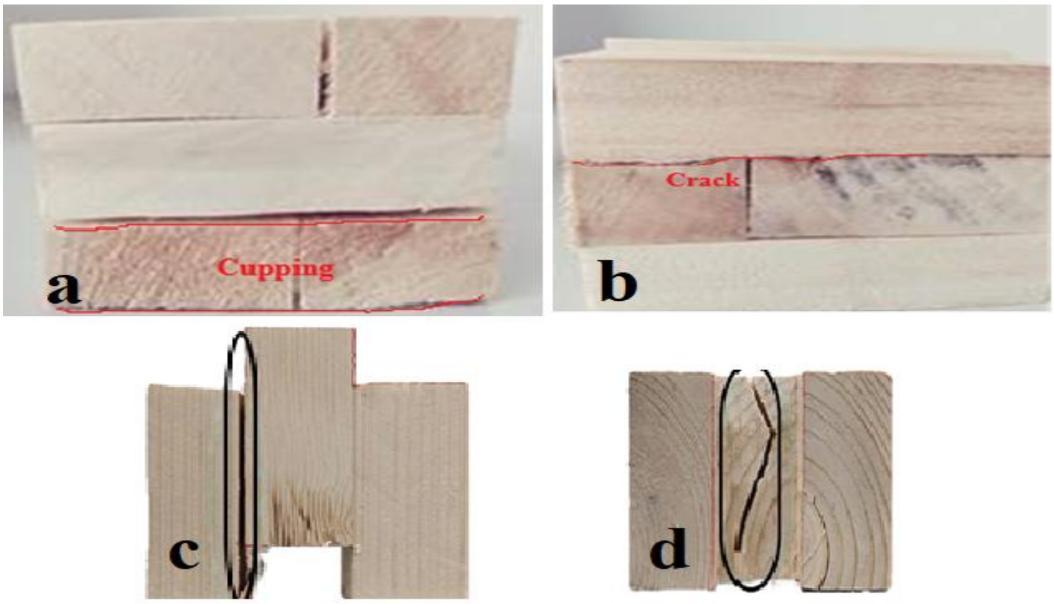

Fig. 8: Delamination failure [a] cupping, [b] crack and shear failure [c] glueline failure at the supporting end, [d] fracture in the core layer.

Fig. 9 depicts the failure patterns of aspen CLT panels under bending (bending and rolling shear test). Although rolling shear at the core layer of the beam in combination with delamination was the prevalent failure mechanism, the sites of fracture initiation and the behaviors of crack propagation through the beams were not the same. Cracks formed near the pressure point in some CLT specimens because of rolling shear and then spread through the beam towards the supports as a delamination mode (Fig. 10a). Rolling shear formed mainly in the middle layer due to the lamellas' transverse layer orientation and the reduced strength of wood across the grain. Due to the lamellas' transverse layer arrangement and reduced strength, rolling shear is the most common failure in bending (Sciomenta et al. 2021; Sousa et al. 2013). CLTs, mainly ME bonded CLT panels, delamination was found near the support due to rolling shear failure (Fig. 10b), similar to the finding of Vetsch (2015) in aspen CLT. Tearing failure was observed in the bottommost layer of some CLT specimens (Fig. 10c), consistent with the results reported by Sousa et al. (2013).

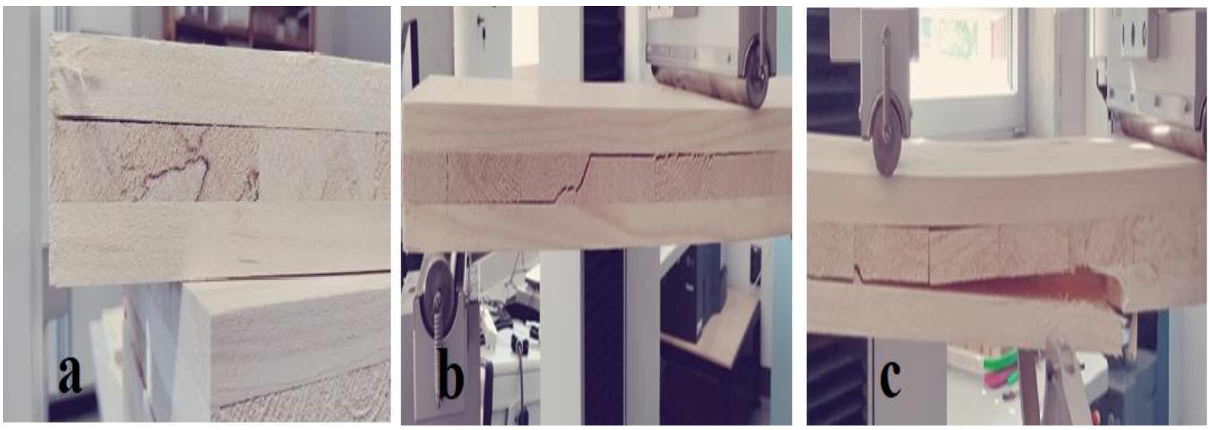

Fig. 9: Bending failure in aspen CLT [a] delamination, [b] rolling shear and [c] tension failure.

Suitability of aspen wood as a raw material for CLT

Tab. 5 represents the measured mechanical parameters of the aspen CLT, including global bending modulus of elasticity (E_{mg}), bending strength (f_m), rolling shear strength (f_r), and bond shear strength (f_v), along with some reference values for CLT panels made of other softwoods with similar or equivalent densities. The reference values in Tab. 4 are the mean values.

Tab. 5: Comparison of properties of aspen CLT with other softwood CLTs with similar density.

CLT Panels	**Modulus of Elasticity (E_{mg})** (N/mm^2)	**Bending strength (f_m)** (N/mm^2)	**Rolling shear strength (f_r)** (N/mm^2)	**Bond shear strength (f_v)** (N/mm^2)
Aspen CLT	7907 – 8183	30.35 – 31.29	1.73 – 2.04	2.8 – 3.2
Irish Sitka spruce (Sikora et al. 2016 a,b)	7583	37.67	1.0 – 2.0	2.8 – 6.1
Southern Pine (Cao et al. 2019; Hindman and Bouldin 2015)	12240	33.62	1.77	4.38
Canadian Hemlock (He et al. 2018)	7670	21.63	1.57	

Tab. 5 clearly shows that the E_{mg}, f_r, and f_v values of aspen CLT are comparable and slightly greater than those of Sitka spruce and Canadian hemlock, two softwood species with comparable densities to aspen. However, the f_m value Sitka spruce CLT was marginally greater by about 10%. Furthermore, in accordance with ANSI/APA PRG 320 (2019), the mean E_{mg} of aspen CLT is only slightly lower (1.4% to 4.7%, based on the adhesive) than the minimal value of E3 Grade CLT (MOE = 8300 N/mm^2). On the other hand, the bending strength (f_m) was much greater than necessary value of E1 Grade CLT (28.2 N/mm^2). Aspen CLT is comparable to southern pine CLT in terms of bending strength (f_m) and rolling shear strength (f_r); however, global bending modulus of elasticity (E_{mg}) and bond shear strength (f_v) were lower, which may be related to southern pine's greater density. From above all it is clear that aspen can be used use as a raw material for CLT manufacturing. The only concern was the delamination failure which had been reported as the most critical tests for evaluating the bond strength of hardwoods by several earlier researches. However, this problem may be solved to a certain extent with higher glue spread or higher-pressure during bonding.

CONCLUSION

This study investigated the suitability of fast-growing aspen (*Populus tremula* L.) wood for load-bearing structures such as CLT panels made with two commercial adhesives, e.g., 1C- PUR and ME. The results showed that aspen wood is a suitable for typical softwood CLT as it met the minimum requirements specified in the standards. The main findings from this research can be summarized as follows: *(1)* Water absorption (*WA*) and thickness swelling (*TS*) depend on the adhesive type. CLT bonded with ME adhesive swelled and absorbed more water than CLT bonded with 1C-PUR adhesive. *(2)* The delamination test was again reported as severe for the aspen CLT panels bonded ME, which can be overcome with higher manufacturing pressure or glue spread. The glue line shear test yielded higher results than the required value mentioned in the standard. *(3)* The global bending modulus of elasticity

(E_{mg}) of 1C-PUR bonded CLT panels were 8183 N/mm^2, which was 3.5% higher than the ME-bonded CLT. The rolling shear and delamination failure were most predominant during the bending and rolling shear tests.

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