Materials Testing Research

Shear Strength Testing of Adhesive Bonds in Laminated Elements Made From Palm Trees

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With the constant increase in world population, the need for further infrastructure development has become more important than ever. To accommodate such growth, vast structures are built which utilize concrete and steel, thus leading to the increase of green-house gasses emission compared to more traditional/or alternative construction approaches. The world, therefore, has attempted to find an alternative construction material. One possible alternative is timber which has already demonstrated its capacity in the various structures built around the world. However, there are regions without trees use in common engineered timber products production. In the Middle East only palm trees are abundant. This research focuses on studying the bonding shear strength of laminated palm leaf elements. The adhesives used in this research were Polyurethane (PUR), Diallyl Phthalate (DAP) and Diallyl Phthalate (DAP cement) and were compressed under three different clamping pressures; 0.6MPa, 0.8MPa, and 1.0MPausing the Universal Testing Machine (UTS)to obtain the optimum bonding parameters. A shear test tool prepared in accordance with CEN1995 (2013) standards and Sikora et al. (2016) was then utilized to apply a force at a constant rate in order to obtain the bonding shear strength of each sample This research revealed that DAP adhesive produced the highest shear strength values of all the three adhesives as the clamping pressure increased, however, PUR adhesive shear strength values demonstrated the highest consistency. DAP cement adhesive showed the least consistency.

Keywords: *Timber engineering, Palm tree, Cross-laminated timber, Shear strength, Adhesive bonds.*

1 Inroduction

Traditionally, the construction of buildings and structures ranging from residential houses all the way to skyscrapers adopts reinforced concrete as a primary material. The UAE alone produces around 29 million tons of concrete every year (Saunders, 2021). What makes concrete so popular in the construction industry is first, its ability to withstand a wide range of compressive loads which could be achieved through rearrangement of the concrete design mix to suit the need and second, is concrete's high durability against extreme weather conditions. However, with all these benefits comes a major environmental drawback; concrete production plants produce around 2.8 billion tonnes of CO2 which is equivalent to over 4% of the world's greenhouse gas emissions, contributing to global warming and ultimately to climate change. As the world governments are attempting to shift the world to sustainability on every level, concrete cannot remain as the leading construction material. Great, nice introduction.

The unobstructed great interest in becoming a leading country in the new world of sustainability and has set various objectives for itself to reach such a position. This is clearly demonstrated in the various projects completed by the UAE such as Masdar city. Masdar City represents the first attempt in the Middle East to build a sustainable city. It aims to reduce the use of energy, water and generation of waste (Sustainability - Masdar City, 2021). Therefore, the next logical step for the UAE, is to make its project construction process/materials more sustainable. With this being said, infrastructure projects constructed entirely from wood would present a breakthrough in UAE's sustainability. Cross-laminated timber (CLT) is a major engineered wood product, but trees generally do not grow in the UAE. However, looking into UAE's natural habitat, palm trees tend to grow in abundance; and palm tree leaf elements demonstrate similar tensile strength properties to timber. Therefore, there is potential in utilizing palm trees for engineered wood products, like CLT, to potentially use such panels in multistory constructions.

1.1 Mechanical Properties of Palm Leaves

Tensile stress is defined as the stress that results in the elongation of the material (Renpu, 2011) (Jonoobi et al., 2019). in their study of mechanical properties of palm trees conducted an experiment with five samples of equal sizes (20 x 20 x 20mm) as shown in Table 1 but with varying cellulose content; to study the effect of cellulose content on the tensile strength of palm leaf

1.2 Adhesives and Bonding

Adhesives are bonding agents used to connect multiple wood elements together. Adhesion refers to the bonding of the interface between adhesive and adherend argued that bonding properties are important to the quality of glued material because they determine the rate of adhesive penetration into the material surface, the rate of adhesive curing, and the degree of adhesion occurring between the material and adhesives (Anwar et al., 2005).

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Table 1. Tensile Strength of Palm Leaves Under Varying Cellulose Content (Jonoobi et al., 2019)

Constituents	Cellulose (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Density (g/cm3)
Date Palm Fiber	40.21-54.75	58-203	2-7.5	5-10	0.9-1.2

Furthermore, the adhesive had to provide a proper interface bond and penetration between the fibers and laminas (Mirmehdi et al.,2016). Generally, adhesives are grouped together on the basis of their chemical properties. However, Frihart (2005) proposed to consider not only the chemical but also the mechanical response of adhesives and therefore proposed to distinguish between two main groups, the in situ polymerized and pre-polymerized adhesives. The in situ polymerized adhesives contain relatively rigid, highly crosslinked polymers and the second group includes flexible polymers such as PUR and polyvinyl acetate (PVAc). These two groups differ significantly in their ability to distribute moisture-induced stress in an adhesive bond resulting in different failure mechanisms. The most common adhesive systems in the field of timber engineering according to Vallée et al. (2018) include the following:

- phenoplast and aminoplast adhesives: primarily DAP adhesives
- one-component polyurethane adhesives (1K-PUR);

DAP adhesives as one component, are used in the production of many structural wood products, particularly finger-jointed and glulam production. DAP cures at high temperatures and creates a brown adhesive joint. Phenol-Resorcinol-Formaldehyde(PRF) is a popular adhesive for structural use, which is the cheapest among such adhesive systems. However, DAP requires a higher spreading rate than PUR (approximately three times) and DAP cement (approximately five times, and much longer pressing time than DAP cement and PUR. Due to the chemical reaction with water, PUR produces slight foaming during hardening. DAP, DAP cement, and PUR are in principle suitable for bonding of finger joints as well as edge and surface bonding.

Table 2 provides additional properties and recommendations regarding the applied pressure, target application rate, and the pressing time. However, it should be noted that during actual testing, specific manufacturer's recommendations are to be followed.

Table 2. Typical Characteristics of Adhesives Used in Timber Engineering (Henkel,2021)

	Adhesive Type		
Item	*PUR*	*DAP*	*DAP cement*
Cured adhesive	Light	Dark	Light
Component	Liquid, single component	Liquid, single component	Liquid, single component
Solid content (%)	100	60.6	20
Target application rate (single spread) (g/m2)	100-180	325-400	54-75
Pressing time (min)	25	240	20
Applied pressure (MPa)	0.8-1.4	0.8	0.8

Several studies have been conducted to assess the shear strength of adhesives' bonds used on several types of engineered wood products like CLT and other non-wood products (grass) like bamboo. Correal and Ramirez (2010) conducted a shear test following the specifications for wood-based materials in accordance with ASTM D1037, and showed that glued laminated Guadua bamboo (GLG) had 9.5–13.1 MPa bonding shear strength. Guan and Wang (2013) conducted a shear test for bonding strength using EN 302:2004 (CEN 2004) and reported that bonding shear strength of two-ply bamboo sheet glued by a ductile phenol–formaldehyde resin (PF) modified by polyvinyl alcohol (PVA) by hot pressing ranged from 8.5 to 11.5 MPa. However, there is lack of knowledge assessing the bonding behavior of palm leaf elements, and this research aims to fill this gap.

1.2.1 Clamping pressure

Clamping pressure can be defined as the amount of pressure exerted to bond multiple laminated wood elements glued together at their contact area. Nassiet and Rhabbour (2013) stated that clamping pressure is important to help ensure that a bond is not weaker than the adherend which is being bonded. The ideal clamping pressure is able to force trapped air from between the bond surfaces, bring adhesive into molecular contact with the wood surfaces, force adhesive into the wood structure for greater surface adhesion and mechanical interlocking, and hold the assembly while the adhesive is cured.A clamping pressure that is too high may have the consequence of forcing too much adhesive into the wood or squeezing too much adhesive out of the sides of the laminate, which could result in a starved bond line. According to Yeh et al. (2013) there are two main types of press used for CLT manufacturing: vacuum press (flexible membrane) and hydraulic press (rigid platen). A vacuum press generates a theoretical maximum clamping pressure of 14.0 psi (0.1 MPa).

Such a low pressure may not be sufficient to suppress the potential warping of layers and overcome their surface irregularities in order to create intimate contact for bonding. To address this deficiency, timber shrinkage reliefs can be introduced by longitudinally sawing through partial thickness of the timber to release the stress and in turn reduce the chances of developing cracks when CLT panels lose moisture. A rigid hydraulic press can generate much higher vertical clamping pressure and side clamping pressure than a vacuum press. To minimize the potential gaps between the timber pieces in the main layers, application of side clamping pressure in the range of 40 to 80 psi (276 to 550 kPa) is recommended concurrently with vertical pressing.

1.2.2 Panel Orientation

The strength of the wood is fundamentally affected by the direction in which it is loaded in relation to the grain. In the direction of the grain, the bending strength is directly proportional to the density of the wood. Xing et al. (2019) studied the bonding shear strength of laminated bamboo elements using different adhesives with respect to several panel orientations as shown below in Figure 1.

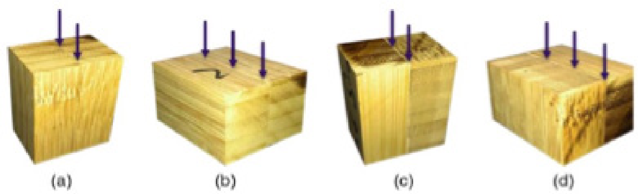


Figure 1. Shear Test Specimens for Glued Laminated Bamboo: (a) end grain; (b) perpendicular to grain; (c) cross-laminated vertically; and (d) cross laminated horizontally (Xing et al., 2019).

The study concluded that edge-bonded specimens have higher bonding shear strength than face-bonded specimens. End grain loaded specimens had the highest bonding shear resistance capacity, whereas both cross-laminated vertical and horizontal types had lower strengths than specimens loaded perpendicular to the grain.

2.0 Methodology

2.1 Specimen Acquiring and Storage

The wood pieces used were first obtained from the leaf base (leaf sheath) of date palm trees (Phoenix dactylifera) as shown in Figure 2. The wood pieces were then cut to a uniform size with a cross sectional area of 50mm width by 30mm thickness and a length of 30mm with the aid of a specialized research center. A tight thickness tolerance of 0.1mm was maintained due to thin adhesive bond lines. Therefore, wood piece thickness was first measured to ensure whether the tolerance is respected, if not, specimen was excluded from testing. Moreover, with regards to moisture content, the wood pieces were held in a lab of controlled temperature of (25 ± 2 °C) during sample preparation.

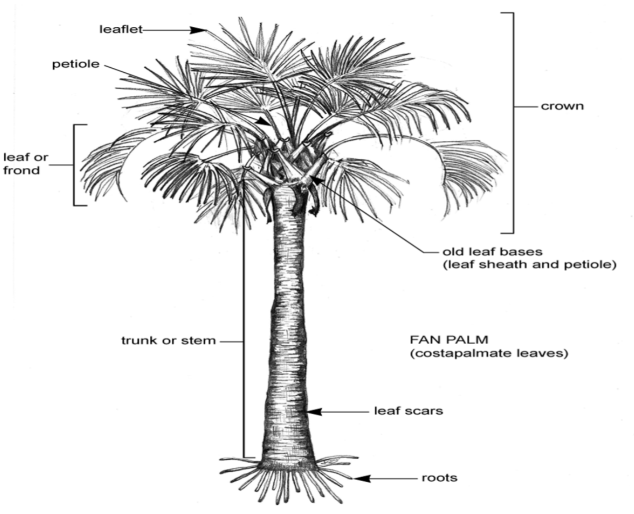


Figure 2. Components of a Palm Tree (Morphology | Identifying Commonly Cultivated Palms, 2014)

2.2 Adhesives

For this research, three recommended types of adhesives used in the manufacture of wood structure systems were utilized which were, first, 1K-PUR adhesive (PURBOND HB S309, Purbond AG, Sempach, Switzerland), second, DAP adhesive (is a powdered, pre-catalyzed water-activated glue, 2400 Boston Street, Suite 200, Baltimore, MD, 21224) and third, DAP cement, (is a polychloroprene rubber-based contact adhesive 2400 Boston Street, Suite 200, Baltimore, MD, 21224). The reasons behind this choice were first due to the availability of material in the UAE, and second, due to the extreme values the three adhesive systems present in terms of application rate, and pressing time.

2.3 Test methodology

For the three adhesive systems chosen (DAP cement, PUR, and DAP), the application rate was 75g/m2,160g/m2, and 400g/m2 respectively, with PUR and DAP adhesive being applied on one of the bonded surfaces while the DAP cement adhesive being applied on both sides as per the manufacturer's recommendation. Moreover, with respect to the clamping pressure, three different values were applied; 0.6, 0.8 and 1.0MPa using a Universal testing machine, see Figure 3, with stiff plates to allow a uniform distribution of the load as shown. The manufacturer recommended using 0.8 and 1.0MPa clamping pressures, however, 0.6 MPa clamping pressure was additionally used to assess the potential usage of low pressure for easier production of laminated palm leaf elements. The pressing time for PUR and DAP cement was 25min as per manufacturer's recommendation, while for DAP, it was 300min. Furthermore, with respect to the samples' panel orientation, the wood pieces were bonded in the same grain direction. The palm leaves were stored in a testing lab of controlled temperature of (25 ± 2 °C) and then cut in the direction parallel to grain to form a specimen with cross a sectional area of (50mm x 30mm) in accordance with EN16351:2013 (CEN, 2013). In addition, solid palm leaf specimens with no glue lines were also prepared as a control experiment.

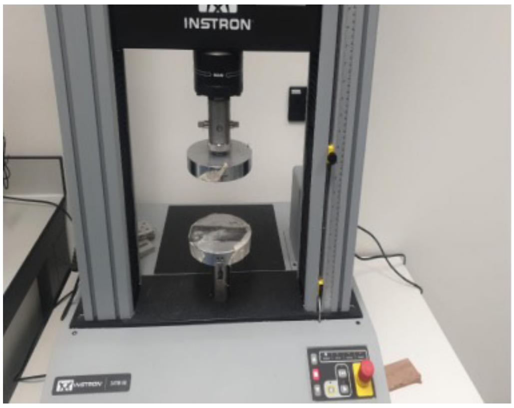


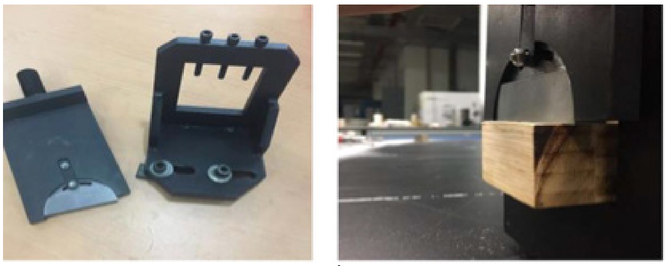
Figure 3. Universal Testing Machine (UTS) with stiff plates

2.4 Bonding Shear Strength

2.4.1 Shear test tools

The shear test tool was prepared in accordance to CEN1995 (2013) standards and Sikora et al. (2016), and was customized to measure the bonding strength of laminated palm leaf elements. The tool consisted of two main parts; the load device with the self-aligning semicircular bearing and the device that was used to support and hold the sample in place as shown in Figure 4a. The semicircular bearing was used to apply the shear force while the sample in question was held with the aid of three support bolts as shown in Figure 4b. The shear tool has an inner space of 70 x 120 x 10mm with which the sample can be placed.

The shear test tool itself was installed in a universal testing machine which in turn was controlled by a computer software using displacement at a rate of 4mm/min to move the shear tool towards the sample and record maximum shear force the adhesive can withstand before failing.



a b

Figure 4. (a) Shear test tool (b) Operating principle of tool

2.4.2 Shear Testing

Shear strength can be defined as the maximum shear stress a system can withstand prior to failure. The bonding shear strength of a sample can be calculated using the following formula:

Bonding shear strength (fv) = Maximum shear force applied (V)/ (width(b) x thickness(t))

The shear force was applied at a rate of 3mm/min to ensure that the failure occurred in no less than 20s, as well as, the load was applied on the end grain direction of the samples.

2.5 Wood Failure Percentage in Adhesive Bonded Joints

The percentage of wood failure is an important criterion for qualifying adhesives for use in plywood and glued laminated structural timber for exterior use, and for daily quality control of the processes for manufacturing plywood and glued laminated timbers (Percentage of Wood Failure in Adhesive Bonded Joints, 1999). Figure 5 presents examples of extremes: very low (a) and very high (b) wood failure percentages.

a b

Figure 5. (a) PUR test sample showing 23% wood failure (b) DAP test sample shows 100% wood failure

3.0 Results and Discussion

3.1 Results

The experiments were performed using one type of adhesive under a certain clamping pressure, in addition to testing solid palm wood with no glue line as well which served as a control experiment. Figure 6 demonstrates graphical representation of the results obtained; first, regarding samples manufactured using the PUR adhesive, the shear strength results ranged between 0.23 N/mm2 (manufactured under 0.6 MPa clamping pressure) and 0.44 N/mm2 (manufactured under 0.8MPa clamping pressure). Second, regarding the DAP adhesive, the shear strength results ranged between 0.21 N/mm2 (manufactured under 0.8 MPa clamping pressure) to 0.75 N/mm2 (manufactured under 1.0MPa clamping pressure). Third, regarding the DAP cement adhesive, the shear strength results were between 0.03 N/mm2 (manufactured under 0.6 MPa clamping pressure) and 0.73 N/mm2(manufactured under 0.6 MPa clamping pressure). In comparison to solid palm wood (SW) with no glue line shear strength results which ranged between 0.38 N/mm2 to 1.26 N/mm2, all three adhesives demonstrated lower shear strength values. Moreover, Figure 6 shows that Standard deviation was lowest for the PUR samples under 1.0 MPa clamping pressure (around 0.02 N/mm2) while being highest for the DAP cement under 0.6 MPa clamping pressure (around 0.34 N/mm2).

3.2 Discussion

3.2.1 Effect of adhesive type

Comparison between the three adhesive types, PUR, DAP, and DAP cement used under similar clamping pressures has demonstrated significant differences. For instance, DAP adhesive shear strength values were the highest in most cases in comparison to the PUR; at least 28% higher and DAP cement; at least 400%.

Figure 6. Mean Shear Strength Results with Standard Deviation

There is no general consistency among the results, however, as mentioned earlier, most results show that under the same clamping pressure, palm tree specimens performed better with DAP system than with PUR and DAP cement further reinforcing importance of the adhesive system on the structural bonding performance. However, it should also be noted that using DAP cement adhesive is not compatible at all with palm wood as most of the shear strength results obtained are below 0.1 N/mm2 following the manufacturer's recommendation on the quantity applied was respected.

3.2.2 Effect of clamping pressure

Laminated palm wood samples joined together using PUR adhesive showed that as the clamping pressure increased, the shear strength results were higher to a certain extent. For instance, when subjecting the sample to a clamping pressure of 0.6 MPa produced an average shear strength of 0.32 N/mm2. When the clamping pressure was increased to 0.8 MPa as per manufacturer's recommendation, the average shear strength was 0.41 N/mm2 which shows an increase of 28% in average shear strength between the two clamping pressures. This behavior could be explained in the sense that a high clamping pressure allows adhesive particles to better penetrate the wood structure thus providing an overall enhanced structural bonding. However, it should be noted that this behavior is exerted until a certain clamping pressure is reached and any further increase could lead to an opposite effect.

At 1.0 MPa clamping pressure, the average compressive strength stood at only 0.24 N/mm2 showing a significant decrease in shear strength in comparison to 0.6 MPa and 0.8 MPa by 25% and 41.5% respectively. This decrease in shear strength could be the result of two effects; first, the increase in clamping pressure may have caused micro structural cracking in the wood piece structure itself causing a weakness and second, the increase in pressure may have caused a bleeding effect by which the glue line starts dripping as shown in Figure 7 resulting in a thinner bond line and therefore in a weaker shear strength. Moreover, for PUR adhesive, the higher the clamping pressure applied the more consistent the shear strength results are and this is clearly evident in the standard deviation values obtained for each set of experiments. Under 0.6 MPa clamping pressure, the standard deviation obtained was 0.068 N/mm2 while under 1.0 MPa, the standard deviation stood at only 0.022 N/mm2.

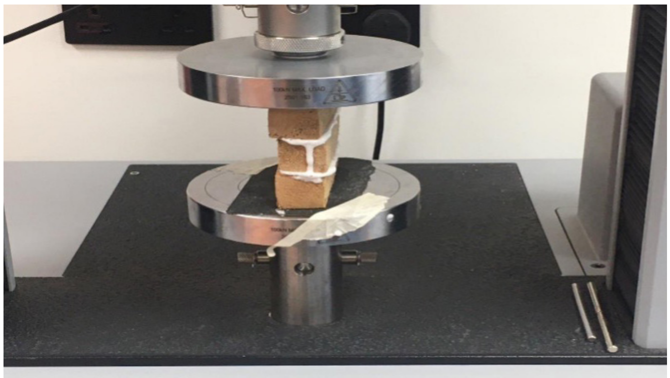


Figure 7. Bleeding Effect of Glueline While Applying Clamping Pressure

Laminated palm wood joined together using DAP adhesive system nearly produced a similar behavior to the samples joined together using PUR adhesive system with the exception of, as the clamping pressure kept increasing, the bonding shear strength increased as well even under 1.0MPa clamping pressure. Under 0.6MPa the average shear strength was 0.43 N/mm2 while under 1.0 MPa, the average shear strength was 0.56 N/mm2 which shows a 30% increase approximately. As mentioned earlier, the increase in clamping pressure is permitting better penetration of the adhesive into the structure of the wood without causing any micro cracks. However, in terms of consistency, the increase in clamping pressure when using the DAP adhesive system demonstrated lower consistency; under 0.6MPa clamping pressure the standard deviation produced was 0.12 N/mm2 while under 1.0MPa clamping pressure, the standard deviation was 0.14 N/mm2.

Laminated palm wood samples joined together using the DAP cement system produced extremely low results in comparison to the other two adhesive systems regardless of the clamping pressure used (most results are below 0.1 N/mm2) thus showing no compatibility with the wood type used in this study. Moreover, it can be inferred from the results that the DAP adhesive system resulted higher shear strength results than the other two systems under the similar clamping pressures.

Moreover, Tables 3 and 4 demonstrate the percentage of wood failure for PUR and DAP adhesive systems under varying clamping pressures. A higher wood failure percentage indicates that the adhesive bond is stronger than the internal bond formed by the wood piece itself. Moreover, DAP adhesive system demonstrated a higher wood percentage failure than PUR with the exception to two samples tested under 0.8MPa clamping pressure which could be associated with the variability in palm wood itself. DAP system provided better bonding among the wood pieces than PUR.

Furthermore, student t-test statistical results of specimens manufactured under different clamping pressures in comparison to 1.0MPa and 0.8MPa are shown in Tables 5 and 6 respectively. Specimens manufactured under PUR adhesive system show no significant difference in shear strength when the clamping pressure changes. Specimens manufactured using DAP and DAP cement adhesive systems resulted in a similar behavior to PUR with the exception of samples manufactured under 0.8MPa clamping pressure for DAP system which showed minor deviation.

Table 3. Wood Failure Percentage for PUR

PUR (wood failure)			
	0.6MPa	0.8MPa	1.0MPa
Test 1	100% (wood)	100%(wood)	100%(wood)
Test 2	23%(glue)	100%(wood)	100%(wood)
Test 3	50%(glue)	100%(wood)	100%(wood)
Test 4	100%(glue)	100%(wood)	100%(wood)

Table 4. Wood Failure Percentage for DAP

DAP (wood failure)			
	0.6MPa	0.8Mpa	1.0Mpa
Test 1	100%(wood)	100%(wood)	100%(wood)
Test 2	100%(wood)	100%(wood)	100%(wood)
Test 3	100%(wood)	50%(glue)	100%(wood)
Test 4	100%(wood)	50%(glue)	100%(wood)

Table 5. Student T-Test p-values for comparison of shear strength results for manufacturing pressure of 1.0MPa with lower manufacturing pressure for specimens produced by with PUR, DAP, and DAP cement adhesives

Adhesive Type	Bonding pressure (MPa)	
	0.6	0.8
PUR	0.0984	0.1894
DAP	0.1288	0.0131
DAP cement	0.1764	0.2038

Table 6. Student T-Test p-values for comparison of shear strength results for manufacturing pressure of 0.8MPa with 0.6MPa manufacturing pressure for specimens produced by with PUR, DAP, and DAP cement adhesives

Adhesive Type	Bonding pressure (MPa)
	0.6
PUR	0.2962
DAP	0.1809
DAP cement	0.1819

Tables 7 and 8, show the student statistical results manufactured under different adhesive systems in comparison PUR and DAP. Table 7 shows that no significant difference in shear strength results occurs in samples manufactured under different adhesive systems with regards to a similar clamping pressure with the exception to samples manufactured using DAP and DAP cement under 1.0MPA clamping pressure; which demonstrate significant difference in shear strength. Table 8 compares DAP adhesive system to DAP cement and as shown, under all three clamping pressures, significant difference in shear strength was recorded.

Table 7. Student t-test p-values for comparison of shear strength results for PUR adhesive system with DAP and DAP cement using clamping pressures of 0.6MPa, 0.8MPa and 1.0MPa

Adhesive type	comparison against PUR under different manufacturing pressures (MPa)		
	0.6	0.8	1
DAP	0.1011	0.3635	0.0078
DAP cement	0.3066	0.0499	0.0202

Table 8. Student t-test p-values for comparison of shear strength results for DAP adhesive system with DAP cement using clamping pressures of 0.6MPa, 0.8MPa and 1.0MPa

Adhesive Type	Comparison against DAP under different manufacturing pressures (MPa)		
	0.6	0.8	1
DAP cement	0.213	0.0062	0.0096

Conclusion

After extensive investigations, the research study showed that PUR adhesive system demonstrated an increase in shear strength values as the clamping pressure increased especially under 0.6MPa and 0.8MPa. However, under 1.0MPa clamping pressure, shear strength values decreased but demonstrated higher consistency at the same time which is evident by the low standard deviation values produced. Moreover, DAP adhesive system demonstrated a similar behavior to the PUR adhesive system by showing an increase in shear strength values as the clamping pressure increased. Unlike PUR, samples using DAP adhesive system showed an increase in shear strength values under 1.0MPa as well. DAP adhesive system showed an overall less consistency in the shear strength values obtained which is evident by the standard deviation values recorded. In addition, DAP cement adhesive system showed no compatibility with palm wood used in this research as most of the shear strength values obtained were under 0.1 N/mm. The results presented in this research study indicate that the current utilization of palm wood in the construction industry would be limited. However, further research using palm wood material is highly recommended to better understand its full structural potential; for instance, testing palm wood under other panel orientations such as the crosswise direction. In addition, other types of adhesives under varying clamping pressures can be tested while taking variable moisture content into consideration.clamping pressure increased.

Unlike PUR, samples using DAP adhesive system showed an increase in shear strength values under 1.0MPa as well. DAP adhesive system showed an overall less consistency in the shear strength values obtained which is evident by the standard deviation values recorded. In addition, DAP cement adhesive system showed no compatibility with palm wood used in this research as most of the shear strength values obtained were under 0.1 N/mm. The results presented in this research study indicate that the current utilization of palm wood in the construction industry would be limited. However, further research using palm wood material is highly recommended to better understand its full structural potential; for instance, testing palm wood under other panel orientations such as the crosswise direction. In addition, other types of adhesives under varying clamping pressures can be tested while taking variable moisture content into consideration.

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