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EVALUATION OF BONDING STRENGTH AND SURFACE QUALITY OF WOOD EXPOSED TO ACCELERATED SOAKING

Zhong ZW[1, *], Ng QL[1] & Hiziroglu S[2]

[1]School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore
[2]Department of Natural Resource, Ecology and Management, Oklahoma State University, Stillwater, OK 74078, USA

**mzwzhong@ntu.edu.sg*

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This work investigated bonding strength of wood from pine, oak and nyatoh, glued with polyvinyl acetate and rubber-based contact adhesive, and exposed to accelerated soaking in water for 2, 4, 6, 12 and 24 hours. The bonding strength of each sample was determined using a universal testing unit. Surface roughness of the samples was also measured using a profilometer. Control samples had the highest bonding strength values for all three types of species. Soaked pine samples did not have any bonding strength for both adhesives, while the rest of the samples had bonding strength reduction. Oak samples had the highest average roughness value of 7.13 μm and the highest bonding strength in all conditions. Data from this work would provide initial information for utilisation of such species in bonding applications where possible water contact is expected.

Keywords: Polyvinyl acetate, surface roughness, bond performance, adhesion, adsorption

INTRODUCTION

Wood is a natural, fibrous and organic material which has been used for a wide variety of applications throughout history. It is still a dominant renewable raw material for furniture and cabinet industries due to its attractive cost and easy machinability. Wood species are distinguished by their unique properties and characteristics. To use wood in the most effective way for engineering applications, specific characteristics such as mechanical and physical properties should be taken into consideration (Miller 2007). One main disadvantage of wood products is their hygroscopic nature which is related to absorption and desorption of moisture from the surrounding environment as a result of changes of relative humidity (Hiziroglu 2004). Wood has some dimensional movement resulting in shrinking and swelling. As such, the moisture content of wood is an important parameter that affects its mechanical properties; for example, bonding strength of wood products can be compromised by moisture-induced internal stresses (Carll & Wiedenhoeft 2009).

Adhesion bonding strength of wood is also a key factor for effective use of wood products for diverse applications. Many studies linked adhesion strength of wood with the chemistry of the adhesive, neglecting the properties of the wood material itself (Frihart et al. 2008). Often, accelerated tests were performed to select between suitable and unsuitable wood adhesives for bonded assembly that is subjected to extreme moisture exposure to have a better understanding of the bonding line durability and adhesive-bond interactions.

Surface roughness of wood is important for quality bonding and finishing treatments. Ultrasonic, optical and stylus type profilometers may be employed to quantify the surface roughness of wood (Zhong et al. 2013). According to previous studies, wood surface roughness may be influenced by grit size of sandpapers, heat treatment and machining (Hiziroglu et al. 2013). Adhesion refers to the interaction between the wood substrate and the adhesive. It often involves both mechanical and chemical aspects which control the ability of the adhesive to hold the surfaces of two woods. One of the mechanisms of adhesion is mechanical locking. Since wood is a porous substrate, its structure provides pathways for the adhesive to penetrate into the cavities and pores of the substrate (Hass 2012). The adhesive has to penetrate deeply enough into the wood, at least covering two to six cells depth so that effective mechanical locking can be achieved. Further penetration into the microstructure of the cell enhances the mechanical interlocking and the surface contact of the adhesive with the wood (Frihart & Hunt 2010).

The adsorption theory is a result of chemical interaction between adhesive and wood substrate on a molecular level where attractive forces are established at the interface. Hydrogen bonding is likely to form due to the interaction of hydroxyl groups in most wood components and polar groups in adhesives, which contributes to both adhesive and cohesive strength (Nordqvist 2012). However, the limitation with the hydrogen bond is that it is generally weakened by water molecules. Bond performance can significantly be affected by two of the physical properties of wood, namely, moisture content and density (Marra 1992). When there is a dimensional change of the wood due to changes in moisture content, stress is induced across bond lines. Density is also considered to be related to strength and it varies among different wood species.

Polyvinyl acetate (PVAc), commonly known as white glue, is usually recommended for use on porous materials and non-structural wood to wood bonds. It is widely used in furniture industry because it is relatively cheap, easy to handle and apply, exhibits high dry strength, and is non-flammable and non-toxic. However, PVAc lacks weather durability and does not have good heat or creep resistance, limiting its wide range of usage (Qiao & Easteal 2001). On the other hand, contact adhesive, which is also known as rubber glue, is widely used by woodworking industry and is recommended for bonding laminates and veneers to woods for countertops and furniture. It is also used for general purposes such as to bond a variety of substrates to one another such as wood, leather and metal (Rowell 2005). Contact adhesive does form strong and durable bonds due to its viscoelastic properties and it is usually very flammable.

Wood species, namely, pine, oak and nyatoh, which are most commonly used for furniture manufacturing in Singapore, were considered in this work. Currently there is very little or no information on surface quality and bonding strength of these three wood species with different types of adhesives as a function of soaking duration in water. Therefore, the objective of this work was to evaluate the bonding strength of the wood specimens bonded with two types of adhesives, namely, PVAc and contact adhesive, and subjected to accelerated soaking tests so that data from this work would be beneficial for better utilisation of the species.

MATERIALS AND METHODS

Solid wood planks of red pine (*Pinus resinosa*), red oak (*Quercus rubra*) and nyatoh (*Palaquim* sp.) (dimensions 44 mm × 20 mm) were obtained from a local supplier in Singapore. A total of 216 samples (six specimens for each species, two pieces of wood per specimen, two types of adhesives and three experiment sets per adhesive), were used for the experiments. Figure 1 illustrates the specimens used for the tests. Initial mass and dimensions of the wood pieces were measured using digital weighing scale and digital vernier callipers respectively and the values obtained were used to determine the average density of each species.

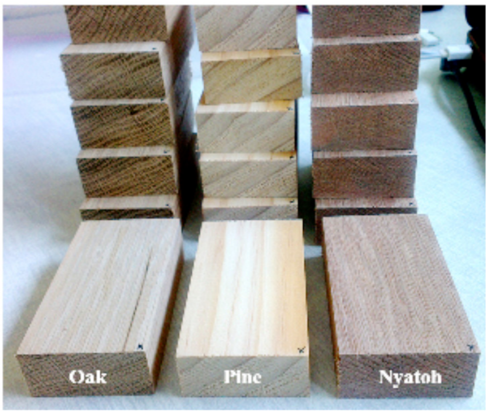

Figure 1 Samples used for the tests

Surface roughness of these wood samples was measured using a stylus type profilometer (Figure 2). Stylus profilometer is able to provide accurate roughness measurement. The profilometer has a 90° diamond stylus tip with a radius of 5 μm. The sampling and assessment lengths used were 0.8 and 4.0 mm respectively. Tracing speed was 0.5 mm s^{-1}. Average roughness, R_a, was chosen to represent surface roughness of the samples in this study. The readings were taken randomly at 10 different positions of each species across the grain orientation.

Figure 2 Position of stylus tip of the profilometer

Samples were then placed in a laboratory oven and dried at 103 ± 2 °C for 24 hours. Masking tape was put on the non-bonded side of the samples to avoid contact with the adhesives during gluing process. Two types of adhesives, PVAc and contact rubber-based adhesive were tested. These are the most commonly used adhesive in terms of their cost and properties. Adhesives were applied to surfaces of samples as uniformly as possible using a brush. Samples applied with PVAc were sealed in plastic bags to minimise large variations in moisture content, and were pressed using weights for 30 min to obtain uniform bonding. Pressing was not required for contact adhesive samples. After the adhesive was applied on both surfaces of the samples, the samples were left to dry partially before they were compressed together for instant bonding.

Prior to the test of adhesion strength, specimens for each type of species and control samples were subjected to accelerated soaking tests. Test specimens were fully immersed in water at ambient temperature for 2, 4, 6, 12, 24 hours in sealed containers. Once soaking was completed, the specimens were rapidly removed from the water and superficially dried using paper towel to eliminate surface water before measuring the mass of the specimens. A shearing test by compression loading was then carried out using a universal testing unit (Figure 3). The crosshead speed of the shearing test was set at 5 mm min^{-1}.

RESULTS AND DISCUSSION

All test results are summarised in Table 1. Oak had the highest average density followed by nyatoh and pine (0.77, 0.69 and 0.55 g cm^{-3} respectively). Oak also had the highest R_a value of 7.13 µm, followed by nyatoh (6.24 µm) and pine (4.02 µm). High roughness values of the oak samples are caused by its porous anatomical structure and high density.

Between the three wood species, pine exhibited the highest moisture content. Moisture content of nyatoh was only slightly higher than oak. This implied that the amount of water absorbed into wood could be highly dependent on the density of the wood where lower density of wood absorbed greater amount of water. Similar results have been reported by Kumar and Flynn (2006).

All swelling percentage values of the samples in the longitudinal, tangential and radial directions were calculated based on the oven-dry dimensions of the wood specimens, which further illustrated the effect of soaking duration on swelling percentage of each wood species. The longer the soaking duration, the higher the swelling percentage of the wood specimens. Oak and nyatoh had lower swelling values than pine based on the measured dimensions thoughout the immersion period. This could be related to the density and anatomical structure of oak and nyatoh. The swelling percentages in the tangential direction were higher than those in the radial directions for all samples. Orientation of microfibrills on the S_2 layer of the cell wall is responsible for the highest tangential movement. Swelling percentages in the longitudinal direction remained relatively constant and the values were much lower, almost negligible, compared with the tangential and radial directions over the same soaking period.

Figure 3 The set-up of the shear strength test

Table 1 Summary of the wood density, average roughness, moisture content, swelling and bonding strength obtained from the tests

Wood species	Density (g cm^{-3})	Average roughness R_a (μm)	Soaking duration (hours)	Moisture content (%)	Swelling (%)			Bonding strength (MPa)	
					Longitudinal	Tangential	Radial	PVAc*	Contact adhesive
Pine	0.55	4.02	0	0.3	0	0	0	1.183	0.775
			2	41.0	0.29	5.77	4.77	0	0.660
			4	44.0	0.30	6.27	5.18	0	0.489
			6	46.1	0.30	6.34	5.19	0	0.435
			12	48.1	0.32	6.76	5.49	0	0.311
			24	49.7	0.34	6.99	5.50	0	0.300
Oak	0.77	7.13	0	0.3	0	0	0	5.832	0.422
			2	5.2	0.13	0.90	0.41	4.210	0.317
			4	6.7	0.18	1.10	0.65	3.929	0.275
			6	9.0	0.18	1.49	0.74	2.337	0.257
			12	12.9	0.18	2.30	2.03	1.251	0.215
			24	15.9	0.18	2.31	2.15	0.789	0.175
Nyatoh	0.69	6.24	0	0.3	0	0	0	3.750	0.454
			2	5.6	0.16	1.01	0.42	2.497	0.366
			4	7.5	0.17	1.27	0.66	2.019	0.293
			6	10.7	0.20	1.67	0.68	1.262	0.277
			12	14.1	0.21	2.42	1.90	0.965	0.267
			24	18.0	0.21	2.47	2.37	0.430	0.222

*‘0’ means that the test specimens produced no shear stress value due to delamination before the test was carried out; PVAc = polyvinyl acetate

Bonding strength of the wood specimens of different soaking durations can be defined by the average of the maximum shear stress obtained from the different sets of experiments for each species at the respective soaking hours. When PVAc was used, bonding strength of pine specimens produced less significant results, as the bonded joint delaminated when soaked in water before shearing test could be carried out. As such, only the bonding strength of the control specimen could be obtained and it was insufficient to determine the relationship between bonding strength and soaking duration. PVAc-bonded pine woods were more prone to glue-joint failure when subjected to soaking (Table 1). They began to delaminate when exposed to water for 1.5 hours. Bonding strength values of the control samples glued together using contact adhesive were lower than those bonded with PVAc. Contact adhesive is rubber-based and has viscoelastic properties. During shear compression test, wood substrates remained intact along the glue line because the adhesive was able to stretch without breaking even though it had already weakened.

However, for oak and nyatoh specimens, shear strength values were much lower when bonded with contact adhesive. For example, at dry condition, shear strength of oak samples bonded with PVAc was 5.832 MPa but was only 0.422 MPa when contact adhesive was used, i.e. a difference of about 93%, while for nyatoh, the difference was 88%. With such huge differences, contact adhesive may not be suitable for oak and nyatoh wood. PVAc adhesive is known for its high dry strength, which is evident in this study.

Another reason why contact adhesive has not been proven satisfactory could be due to the high viscosity of the contact adhesive itself. The formation of the thick layer of adhesive due to high viscosity of glue prevented any close contact between wood surfaces and the adhesive. As such, it could not provide enough mechanical interlock between the wood substrates. Glue with high viscosity can wet only the protrusions of the surface, which leads to a reduction in the bonded area and eventually reduces bond strength. This supported the findings in this study whereby overall bonding strength of contact adhesive was much lower than PVAc.

Oak displayed the highest bonding strength between the three wood species when bonded with PVAc, followed by nyatoh and pine. Oak had the highest density and surface roughness compared with the other two species. Rougher surfaces developed better mechanical interlocking between adhesive and wood substrate during curing. It also increased the physical contact area, which in a way formed better glue line. Based on the adhesion performance analysis, PVAc better adhered to rougher surfaces, resulting in higher adhesion strength. Surface roughness has positive correlation with bonding strength of wood (Hiziroglu et al. 2014). Based on the data acquired, it appeared that the bonding strength of all three wood species decreased with increasing soaking duration. Shear strength values for soaked specimens were much less than the dry shear strength for both adhesives.

Swelling contributes to dimensional instability and hence the decrease in bonding strength of wood as a result of water-soaking. As mentioned earlier, the longitudinal swelling was negligible in this study. The tangential movement of the samples was always higher than that of radial. These higher swelling could be partly attributed to the presence of rays in the radial orientation, which restrained the movement in that direction. Swelling occurred as a result of changes in wood moisture content. This caused moisture-induced internal stresses in wood which influenced bond durability. These induced stresses then caused cracks in the wood specimen at the bonded interface (Frihart et al. 2008), as observed in this study. Eventually, adhesive bond-line failure occurred, and bonding strength decreased when exposed to high humidity or a wet environment.

CONCLUSIONS

Stylus-type equipment is able to quantify the surface roughness of wood species. Pine had lower density and the smoothest surface, while oak and nyatoh had higher density and rougher surfaces. These defects could cause imperfect bonding, which also contributed to the lower bonding strength of the specimens. Moisture content and swelling of pine, oak and nyatoh specimens increased with soaking duration but bonding strength decreased for both adhesive types. PVAc adhesive resulted in higher bonding strength under dry condition for the three wood species. Under wet conditions, oak and nyatoh bonded better with PVAc adhesive compared with contact adhesive. However, PVAc adhesive should be avoided for gluing of pine wood when used for outdoor applications because water soaking resulted in zero bonding strength. Contact adhesive could be used to bond softwoods such as pine when exposed to high moisture because of its water resistance and high glue strength.

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