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THE BENDING AND TENSION STRENGTH OF FURNITURE JOINTS BONDED WITH POLYVINYL ACETATE NANOCOMPOSITES

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ABSTRACT

Furniture is the general name given for the portable equipment used in various human activities such as seating, working and relaxing. They can be a product of design and is considered a form of decorative art. They can widely be manufactured with different adhesives. Biodegradable and bio-based adhesives which have no toxic compounds and non-dangerous elements have been selected since the furniture is generally benefited in interior locations. Meanwhile, polyvinyl acetate (PVAc) is a thermoplastic polymer which is widely used in the furniture industry. In this study, tension and bending strength of the furniture joints bonded with polyvinyl acetate adhesives filled with nano-TiO_2 and nano-SiO_2 were investigated. Three materials; oak (*Quercus robur*) wood, beech (*Fagus orientalis*) wood and plywood made with beech veneers were selected, and the joints were prepared by mortise and tenon joints. The results showed that the maximum value for the tension strength and bending strength were obtained to beech wood and oak wood in 2% addition of nano-SiO_2 fillers. The minimum values for the tension and bending strength nano-SiO_2 were found to plywood and 4% loading.

Keywords: Biodegradable polymer, bonding performance, furniture, *Fagus orientalis,* mechanical properties, plywood, *Quercus robur*.

INTRODUCTION

In wood manufacturing, each processing step affects the material utilization and the cost efficiency such as cutting, planning, etc (Broman and Fredriksson 2012, Belleville *et al.* 2016). Adhesives constitute a significant portion of the total cost of wood furniture (Clinton *et al.* 2006, Hicks 2005). Therefore, it is important to use effective adhesive in furniture production. The adhesive used play important roles in providing strength to the joint (Kumar *et al.* 2015, Abdolzadeh *et al.* 2015). Several methods to improve the strength of adhesive joints have been investigated (Park et *al.* 2009, Aydemir 2015). The joints are generally recognized as being the weakest points in the construction since the forming profiles of the joints prevent the development of the full strength of the material (Tankut and Tankut 2011). Calculating the load bearing capacity and the strength of the joints is a complex problem depending on many factors. The most significant of these factors are the strength of the construction material, the method of loading, the strength of glue lines appearing in the joint, and the wood cross section as reduced by the joints profile (Eckelman 2003, Eckelman and Erdil 2000, Smardzewski and Papuga 2004). The strength of wood construction materials have been determined by many investigators and are satisfactory for practical purposes (Vassiliou and Barboutis 2008, Dai *et al.* 2008). There are also many data technical reports on the load bearing capacity and strength of furniture joints (Ho and Eckelman 1994, Zhang *et al.* 2005). The properties and types of glue lines in joints (and the factors influencing their mechanical properties (Bowyer *et al.* 2003, Veselovsky and

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Kestelman 2002) have also been determined. The mechanical properties and factors affecting the glue lines have been arranged into a group of technological features and a group of strength features (rigidity and load bearing capacity of joints, stresses in main glue lines, size of glued surfaces, anatomic surface of joined members (Eckelman 1990). Many adhesives such as PVAc, Polyurethane (PU), Epoxy (E), Polyvinylchloride (PVC) etc were used in furniture manufacturing. PVAc is a biodegradable polymer which has major advantages such as good mechanical and thermal properties, high functionalities, biodegradability, biocompatibility, and many applications (Shchipunov 2012, Rhim and Ng 2007, Zhai *et al.* 2008). They have many applications such as woodworking parts, packaging industry, textile raw material etc. Many studies have provided great improve for obtaining much high performance with adding of nanoparticles into polyvinyl acetate. Nano fillers exhibit many important advantages as compare with macro/micro fillers for adhesive reinforcing. The formation of stable chemical linkages between the nano-SiO_2 and the polymer improve the heat resistance, radiation resistance and mechanical properties of polymer (Fu *et al.* 2014).

The aim of study is to determine the effects of the nano filler loadings such as nano- TiO_2 and nano-SiO_2 on the bending and tension strength of the T-type joints (mortise and tenon joints). Nano-TiO_2 and nano-SiO_2 have unique structure and properties, and very high elastic modulus. Therefore, they were selected to improve the properties of the PVAc. The bending strength, moment bearing capacity at bending, and tension strength of T type joints bonded with PVAc adhesives filled with nano fillers at different loading rates (1%, 2%, and 4%) were investigated.

MATERIAL AND METHODS

Materials

Silicon dioxide, or Silica (SiO_2) and Titanium oxide (TiO_2) were supplied by mknano (Canada). Silicon dioxide (MKN-SiO_2-015P: Hydrophilic SiO_2) was amorphous and 99,5% pure. The size of SiO_2 is 15 nm. Titanium dioxide (MKN-TiO_2-R050L) was hydrophilic (with SiO_2 coating) and 99% pure. The size of TiO_2 is 50 nm. PVAc has a 1200 polymerization degree and a 90% hydrolysis level. The PVAc was supplied by Hafele Inc. of Turkey. The color and viscosity of PVAc was white and 9,21 Ps.s for +20^{o}C. The solid content and density of PVAc used were 50% and 1090 kg/m^3. The beech wood, oak wood, and plywood were selected to commonly be used to furniture frames in Turkey. Density and moisture content of the materials were given in Table 1.

Table 1. Density and moisture content of the materials.

Materials	Density (Air-dry) (kg/m³)	Moisture Content (%)
Beech (*Fagus orientalis*)	720	10,23
Oak (*Quercus robur*)	730	11,50
Plywood	690	9,48

Preparing the PVAc composites with nano-SiO_2 and nano-TiO_2

In composite preparation, the process steps were conducted according to similar studies (Zhai *et al.* 2008, Kaboorani *et al.* 2013). Nano-TiO_2 and nano-SiO_2 were solved with distilled water with ultrasonic mixer for 20 min (Force: 50 watt and %50 frequency). The obtained solution was added to PVAc matrix, and blended with mechanical mixer at 800 rpm for 20 min, later ultrasonic mixer at 50 watt and % 50 frequencies for 20 min, and finally mechanical mixer at 800 rpm for 20 min. The blends were successfully prepared by solution method using various loading rates (1%, 2%, and 4%) of nano fillers.

Preparing of mortise and tenon joints with nano fillers/PVAc composites

The mortise and tenon joints are still widely used by both small and large manufacturers, and hence there is a need to define the parameters that define their performance. For this, Beech (*Fagus orientalis*), Oak (*Quercus robur*), and plywood, which have 17 sheet with 1,5 mm thickness according to EN 14374 were used. These materials were dried in a drying chamber for 65% and at 20^{o}C in wood mechanic laboratory, Bartin University. These wood materials were dimensioned as 450 mm × 30 mm × 25 mm for leg and 350 mm × 55 mm × 25 mm for rail in a local timber plant. The bending test in mortise and tenon joints was conducted according to Eckelman (2003). With five replicates for each combination of the main factors the experiment contained 7x3x5 = 105 joints (Table 2). 210 samples were totally used in the tension test (105 samples) and bending tests (105 samples). Figure 1 show the dimension of mortise and tenon joints.

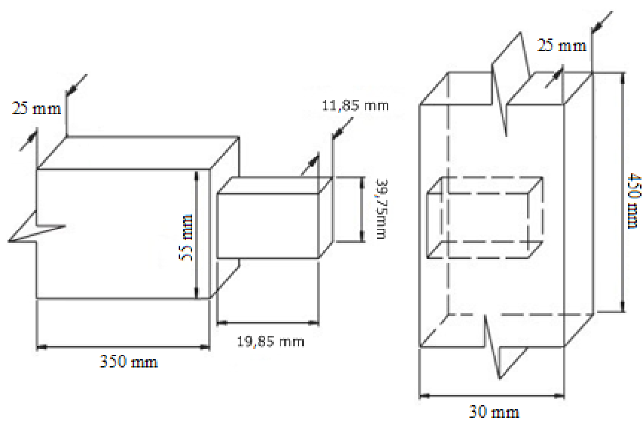

Figure 1. The dimension of mortise and tenon joints.

The machined parts were stored at 22 ^{o}C and 65% RH for 2 months before assembly. Polyvinyl acetate (PVAc) glues filled with nano-TiO_2 and nano-SiO_2 was used for the assembly of the joints used in this study. The glue was applied both to the mortise and to the tenon to ensure complete coverage so that any variations in strength could be attributed to the geometrical construction of the joint rather than to erratic assembly conditions. After gluing, each joint was clamped up with just enough pressure to bring the rail shoulder into contact with the face of the mortise for not more than 1 min while the excess glue was removed. The sample codes in the bending and tension test were given Table 2.

Table 2. The samples codes.

PVAc formulations	Loadings of fillers (%)	Materials used for Joints	Samples code	Sample replicate
Neat PVAc	0	Beech	NB	5
		Oak	NO	5
		Plywood	NP	5
PVAc + SiO_2	1	Beech	S1B	5
		Oak	S1O	5
		Plywood	S1P	5
	2	Beech	S2B	5
		Oak	S2O	5
		Plywood	S2P	5
	4	Beech	S4B	5
		Oak	S4O	5
		Plywood	S4P	5
PVAc + TiO_2	1	Beech	T1B	5
		Oak	T1O	5
		Plywood	T1P	5
	2	Beech	T2B	5
		Oak	T2O	5
		Plywood	T2P	5
	4	Beech	T4B	5
		Oak	T4O	5
		Plywood	T4P	5
			Total	105

Methods

In this study, the Universal test machine was fitted with a cast aluminum alloy angle plate to support the vertical leg member of the joint while the horizontal rail member was loaded by means of a stirrup attached to the machine crosshead, which was raised 4 mm min^{-1} during the test according to the method represented and used by Eckelman 1970, Eckelman *et al.* 2004. Rate of machine-head loading in both cases was 5 mm/min. The ultimate moment capacity of the joint is calculated as the product of breaking load and the distance between the point of application of the load and the face of the joint during bending test. The ultimate moment capacity is, in fact, the bending moment required to break the joint and it is expressed in units of N.mm In this study, the moment arm (L = 240 mm) was measured from the point of load application to the face of the joints. The test setup for the bending tests was given in Figure 2, Ultimate moment capacity, *f*, was calculated as Eq. 1:

$$f = F \ x \ L \ (N.mm)$$

where F is the applied load (N).

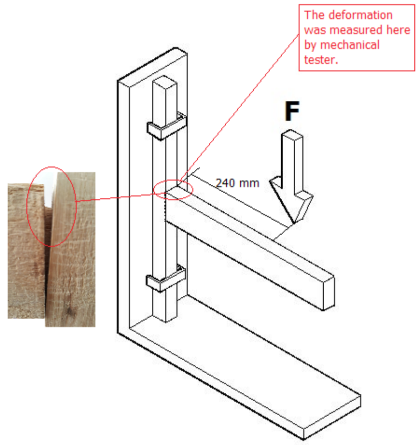

Figure 2. The test setup for the bending tests.

Tension test was carried out according to Barboutis and Meliddides (2011) and Erdil *et al.* (2005). The maximum force data of samples was recorded. The test setup for the tensile tests was given in Figure 3.

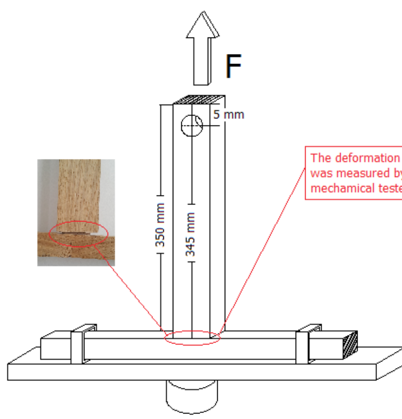

Figure 3. The test setup for the tensile tests.

RESULT AND DISCUSSION

The average values, maximum bending moment capacity (MBMC), maximum bending (MBS) and tension strength (MTS), standard deviation and variation coefficient for bending/tension test of mortise-tenon joints bonded with nano particles filled PVAc nanocomposites were presented in Table 3.

Table 3. Results obtained from bending and tension tests of mortise-tenon joints bonded with nano particles filled PVAc nanocomposites.

Formulation Code	Maximum Bending Moment Capacity-MBMC (N.mm)		Maximum Tension Strength-MTS (N)		
	$\overline{X}$	S	$\overline{X}$	S	V
NB	70944	11526	3218	106	3
NO	73968	11657	3577	360	10
NP	65232	9798	2485	427	17
S1B	79020	11278	3679	643	17
S1O	79536	8709	3704	503	13
S1P	73829	9970	3114	589	18
S2B	86280	5863	4134	303	7
S2O	88272	5297	4051	614	15
S2P	81744	7369	3041	427	14
S4B	55140	10756	2816	526	18
S4O	58660	845	2810	330	11
S4P	48100	710	2087	257	12
T1B	85920	862	3760	570	15
T1O	86020	649	3864	600	15
T1P	74780	1050	3012	440	14
T2B	81060	827	3482	492	14
T2O	81740	1256	3572	456	12
T2P	69410	543	3011	283	9
T4B	67820	924	3065	540	17
T4O	70080	1011	3422	621	18
T4P	67390	799	2395	441	18

X (N), S (±) and V (%) show average of the values, standard deviation and variation coefficient, respectively.

The highest MBS, MBMC and MTS values were obtained for samples with the oak wood in 2% addition of nano-SiO_2 fillers samples. The lowest MBS, MBMC and MTS values were occurred when was used the plywood in 4% addition of nano-SiO_2 fillers. Results showed that the nanoparticles (SiO_2, TiO_2) mixing had a positive effect on the bonding strength of PVAc at 1% to 2% loadings.

As compare with control samples, the change ratios in the MBS, MBMC and MTS with loadings of nano-fillers were given in Figure 4.

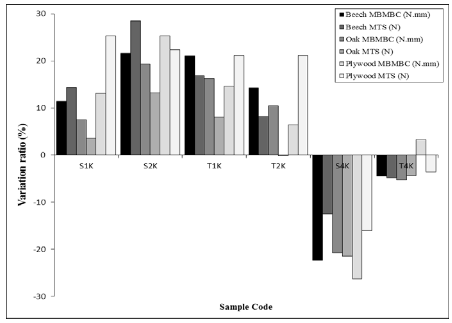

Figure 4. Change ratios (%) of MBS, MTS and MBM of mortise and tenon joints.

The multi-way ANOVA analysis was conducted to find the effect of nano-fillers type, the filler loadings, and material types on bending strength of the mortise and tenon joints, and the obtained data were given in Table 4.

Table 4. The multi-way ANOVA analysis done for the effects of nano-fillers type, the filler loadings, and material types on Bending Moment Capacity of the mortise and tenon joints.

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	1,145E10a	20	5,724E8	6,849	0,000
Intercept	5,127E11	1	5,127E11	6,134E3	0,000
Nano particle type (A)	2,899E8	1	2,899E8	3,468	0,066
Material type (B)	1,202E9	2	6,011E8	7,191	0,001
Filler loadings (C)	7,465E9	2	3,733E9	44,655	0,000
A * B	1,125E7	2	5624320,000	0,067	0,935
A * C	1,910E9	2	9,550E8	11,426	0,000
B * C	5,465E7	4	1,366E7	0,163	0,956
A * B* C	1,957E8	4	4,892E7	0,585	0,674
Error	7,021E9	84	8,359E7		
Total	5,859E11	105			
Corrected Total	1,847E10	104			

According to the multi-way ANOVA analysis, it was found that the material type (B) and the fillers loadings (C) was statistically be important at 0,05% of significant level, whereas it was found that the difference among the nano particle type (A) was significant not important. The interaction of nanoparticle type with the filler loadings were statistically significant rate on the bending strength. Duncan test was applied to determine the differences between groups. The effects of material type on the bending strength were given in Table 5

Table 5. Duncan test results for the effect of material type on the Bending Moment Capacity.

Material type (B)	**Average Maximum Bending Strength (N.mm)**	Groups
Beech	74996	A
Oak	76896	A
Plywood	68639	B

The effect on the bending strength of filler loadings are shown in Table 6 according to Duncan test results.

Table 6. Duncan test results for the effect of filler loading on the Bending Moment Capacity.

Filler loadings (%)	Average Maximum Bending Strength (N.mm)	Groups
0	70048	B
1	79728	A
2	81296	A
4	61239	C

The multi-way ANOVA analysis was conducted to find the effect of nano-fillers type, the filler loadings, and material types on tensile strength of the mortise and tenon joints, and the obtained data were given in Table 7.

Table 7. The multi-way ANOVA analysis conducted for the effects of nano-fillers type, the filler loadings, and material types on tensile strength of the mortise and tenon joints.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3,004E7	20	1,50E4	6,68	0,00
Intercept	1,003E9	1	1,003E9	4,4E5	0,00
Nano particle type (A)	5792,04	1	5792,04	0,026	0,87
Material type (B)	1,379E7	2	6893306,01	30,68	0,00
Filler loadings (C)	1,185E7	2	5925477,38	26,37	0,00
A * B	177302,96	2	88651,48	0,39	0,68
A * C	2271540,62	2	1135770,31	5,05	0,01
B * C	118375,18	4	29593,79	0,13	0,97
A * B* C	618738,78	4	154684,69	0,69	0,60
Error	1,888E7	84	224723,93		
Total	1,160E9	105			
Corrected Total	3,004E7	20	1501772,88	6,68	0,00

According to the multi-way ANOVA analysis, it was found that the material type (B) and the fillers loadings (C) was statistically be important at 0,05% of significant level, whereas it was found that the difference among the nano particle type (A) was significant not important. The interaction of nanoparticle type (A) with the filler loadings (C) were statistically significant rate on the tension strength.

Duncan's test was applied to determine the differences between groups. The effect on the tension strength of material type of factors Duncan test results are shown in Table 8.

Table 8. Duncan test results for the effect of material type on the tension strength.

Material type (B)	Average Maximum Tension Strength (N)	Groups
Fagus orientalis	3571	A
Quercus robur	3450	A
Plywood	2734	B

The effect of filler loadings on the tension strength Duncan test results are shown in Table 9.

Table 9. Duncan test results for the effect of filler loading on the tension strength.

Filler loadings (%)	Average Maximum Bending Strength (N)	Groups
0	3093	B
1	3522	A
2	3548	A
4	2766	C

The results showed that while the loadings of the nano- SiO_2 and nano- TiO_2 increased from 1% to 4% for both tensile and bending strength have increased loading at 1% and 2%, but it decreased to the loadings at 4%. In papers of Park *et al* .(2009), Mirjalili (2014), it was stated that polymers generally exhibit the enhanced mechanical properties as filling the low loading of nano-fillers due to homogenously dispersion of the fillers, whereas at high loadings, the mechanical properties generally decrease due to heterogeneously dispersion and some aggregations in polymer matrix. The improving in the adhesion can be explained with good interactions between nano-fillers at low loadings (due to good dispersion) and polymer matrix (Zhai *et al.* 2008, Bardak *et al.* 2016). Strength of the composite materials having to strong interphase interactions is high, whereas, their flexibility is low. Strength of the composite materials having to poor interphase interactions is low, and fracture strength is high (Zhai *et al.* 2008). It can be said that this status increase the bonding performance of the joints. According to the material type used, it was found to be not statistically difference between beech and oak woods as comparison with plywood, but the largest value of both bending and tension strength in the all formulations was obtained to oak wood. This status can be said due to the anatomical structure of solid wood (Tankut *et al.* 2014, Uysal *et al.* 2005).

CONCLUSIONS

This study conducted to improving the bending and tension strength of the mortise and tenon joints with adding the different loadings of nano- fillers to PVA matrix. The obtained results showed that addition of TiO_2 and SiO_2 for 1% and 2% to PVAc improved the performance of the joints, but the loading with 4% to the matrix was found to decrease due to aggregation. According to materials type, the largest values were obtained as beech and oak woods, whereas, the lowest values were the plywood. Nano-fillers affected the bonding strength of PVAc with different loadings. At low loadings, nano-fillers were generally dispersed well in the PVAc and at high loading, some aggregates were observed. When a good dispersion of nano-fillers was provided at the low loadings, bonding properties of PVAc was found to improve. Consequently, nanoparticles may provide a means to achieve strong joint for furniture applications.

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