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THE EFFECT OF HUMIDITY ON THE SHEAR STRENGTH OF GLUED WOOD BASED AND PLASTIC JOINTS

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ABSTRACT

The main objective of the paper is to determine the effect of humidity on the mechanical properties of glued structural joints. Shear strength of glued joints is investigated in terms of two environments with specific climatic conditions, it means dry environment of residential and public building interiors at the tempeature of t = 23 ± 2°C, and relative humidity of WR = 45 ± 5% and wet environment at the temperature of t = 23 ± 2°C, relative humidity of WR = 90% ± 5% (bathrooms, laundries, swimming pools). Two types of materials, including their combination, particle board (PB) with the thickness of 12 mm and artificial stone (plastic material) with the thickness of 12 mm were tested. Epoxy and polyurethane adhesives were used for glued lap joints. In general, the air humidity of the environment does not have a statistically significant effect on the shear strength of the glued joints. For bonding the same materials, the maximum value of shear strength were achieved using polyurethane (PUR) adhesive and the material combination – plastic-plastic and air humidity of 90%. For bonding materials with various properties (PB and plastic) epoxy adhesive is the most suitable.

Key words: shear strength, glued joints, humidity, particle board, artificial stone (plastic material).

INTRODUCTION

The adhesive transfers the stress from one bonded element to another by shear stress. Therefore, the shear strength test of the glued joint is used to evaluate the efficiency of glued joints. In addition to the shear strength, the percentage of damage to the wood (glued material) on the fracture surface is also evaluated. Higher degree of rigidity is assumed when using structural adhesives in comparison to glued wood. It can be a prerequisite for measuring the percentage of estimated wood failure. Therefore, properly made joints should be broken in wood and not in a glue line. Owing to the fact, the measurement of percentage of wood failure after the shear strength test should provide a qualitative glued joint efficiency indicator.

The joining processes play an important role in woodworking and furniture manufacturing industry. They make possible to create durable joining technology of structural elements as well as new materials and, last but not least, the aesthetic valuation of structural parts. However, the quality of the bonded materials is affected by many factors, for example moisture of the glued material – wood.

The authors BOMBA *et al*. (2014) investigated the impact of wood moisture on the strength of glued joints made using PVAc PUR adhesives. It was found out that in addition to actual moisture content of bonded wood, the quality of joint is also affected by the environment which the glued joint is subsequently subjected to. In the standard environment, the strength of tested joint using PVAc adhesive decreases with increasing moisture content of wood but it still meets the requirements of the standard. In the humid environment, the strength falls below the limit value of the standard. In the standard environment, the strength of joint bonded with PUR adhesive is similar, but the decrease in strength is lower. In the humid environment, the highest strength is at the wood moisture content of 20% and meets the requirements for specific standard minimum strength (4 MPa). Graphs were created following the measured values and show the influence of wood moisture content on the final bond strength of a joint clearly. The modified method for shear strength measurement of adhesive bonds in solid wood was examined in the article DERIKVAND *et al*. (2016). Based on the results, the impact of testing method on the estimation of adhesive bond strength is more significant when the ultimate shear strength of the adhesive bond reaches the shear strength parallel to the grain of wood. In addition, testing method has much less influence when the adhesive bond strength is low.

Investigations of quasi-static and fatigue failure in glued joints subjected to tensile shear loading were observed by BACHTIAR *et al.* (2017). Lap joints of beech wood (*Fagus sylvatica* L.) connected with four different types of adhesives; polyurethane (PUR), melamine urea formaldehyde (MUF), bone glue and fish glue were experimentally tested until the failure of specimens. The average shear strength obtained from the quasi-static test ranged from 12.2 to 13.4 MPa. These findings do not indicate any impact of the different adhesive types. Only the results of the fatigue tests carried out at different stress excitation levels between 45% and 75% of the shear strength show the influence of the adhesives. In general, the performance of animal glues and MUF were similar in both quasi-static and fatigue loading under dry conditions. Comparison of shear strength in lap and scarf joints and the effect of wood species are discussed by KONNERTH *et al*. (2006). Following the results, the fact that glued joint failure occurred in wood in scarf joint testing and using lap joint the failure occurred in the glue line of the specimens can be concluded. However, due to mixed mode loading and enhanced penetration, scarf joint testing is not suitable for determining the absolute dry adhesive shear strength.

The study of BEKHTA *et al*. (2015) is aimed at the laboratory investigation of bonding birch veneers (*Betula pubescens Ehrh*.) with high moisture content (15%) using modified phenol-formaldehyde (PF) resin. Wheat starch, rye flour, resorcinol and phenol-resorcinol-formaldehyde resin were chosen as modifying agents. Dynamic viscosity, hydrogen ions concentration, solid content, curing time, pot life of developed adhesive compositions and shear strength of plywood specimens were analysed. ANOVA analysis showed that type, mixture and content of modifying agents affect the mechanical performance of plywood panels significantly. The obtained results of shear strength values were above the standard requirements (1 N/mm2), and the properties of specimens met the European standard EN 314-2 for bonding quality of class 3, therefore, such plywood panels can be used in exterior conditions.

Not only joining the wood itself, but also bonding the wood with other materials is of great importance today when new materials are being developed. The properties of glued joints of non-wood materials can be evaluated following the results of the study of MACHALICKÁ *et al*. (2017). Her research is aimed at the investigation of glued joints in glass load-bearing structures considering the effect of various substrates (glass, steel, stainless steel, aluminium) and their surface treatment (sandblasting for the glass surface) on the adhesion of selected adhesives. Moreover, the thickness of the adhesive layer and the effect of artificial ageing are also discussed. Tensile and shear tests were carried out using three sets of specimens with various adhesives and substrates – two sets for tensile and shear testing and one set for shear tests on specimens exposed to ageing. The results show that sandblasting of the glass surface can improve the adhesion, and thus, the strength values of an adhesive joint in cases where, with a smooth glass surface, cohesive failure is not reached. Thickness of the adhesive layer had a significant effect on semi-rigid acrylate adhesive, where the joint achieved higher strength values with less thickness of the glue. The effect of ageing varied according to the adhesive. The paper of TAIB *et al*. (2006) deals with glass-fiber-reinforced vinylester composite laminates manufactured by resin infusion and bonded with epoxy adhesive. The effect of joint configuration, adhesive layer thickness, defects, humidity, spew fillet and adherend stiffness were investigated using the tension tests. Investigation of the spew fillet and adherend stiffness for the lap joints showed that the spew fillet effect was dependent on the adherend stiffness and adhesive ductility, respectively.

MATERIAL AND METHODS

Test Specimens

Test specimens were made of two basic types of materials: particle board (PB) with the thickness of 12mm and plastic-based material called Stonez Quarz Surface - Staron® with the thickness of 12mm. Three sets of test specimens with these material combinations: plastic + plastic, PB + PB and plastic + PB were created.

Shear strength of the joint was determined using the specimens conditioned under laboratory conditions for dry environment (t = 23°C ± 2°C, WR = 45% ± 5%) and wet environment (t = 23°C ± 2°C, WR = 90% ± 5%). The specimens were conditioned for 28 days. For all sets of material combinations and given climatic conditions, two types of adhesives were used – one-component reactive adhesive based on polyurethane PUR Leim 507.0 and two component adhesive CHS-EPOXY 371 (1200).

Shape and dimensions of the test specimens were determined in accordance with the standard ČSN EN 1465: 2009 (Fig. 1). Length of the lap is 30mm and the size of the glued area is S = 0.0006 m^2.

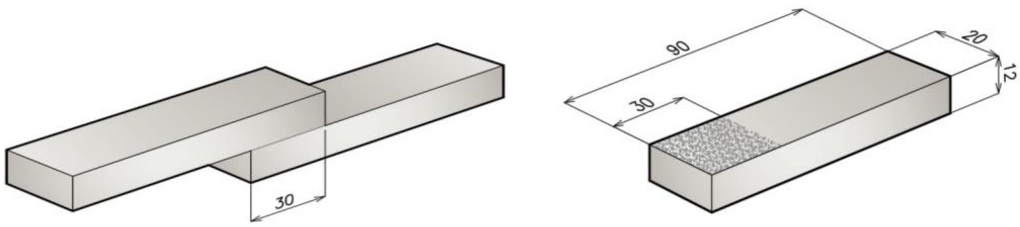

Fig. 1 Shape and size of specimens to determine shear strength under tensile stress (ČSN EN 1465: 2009).

Principle of the Test

Tests were performed using the test device in accordance with the standard ČSN EN 1465 which specifies the method to determine shear strength under tensile stress of the lap glued joints (Fig. 2).

The shear strength value was calculated according to the equation:

$$\tau = \frac{F_{max}}{S},$$

where:

τ – shear strength (MPa)

F_{max} – maximum force (N)

S – loaded glued area of the specimen tested (mm^2), $S = b \cdot l$ where b (mm) and l (mm) are dimension of glued area

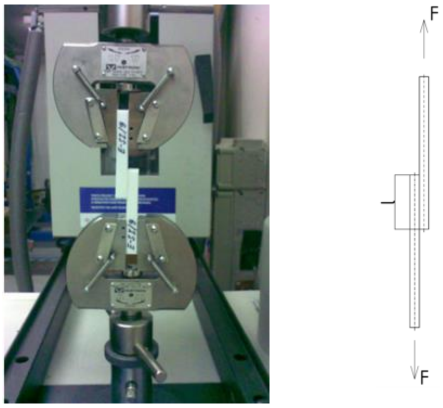

Fig. 2 Principle of the test to determine shear strength (ČSN EN 1465: 2009).

RESULTS AND DISCUSSION

Moisture penetrates into the joint through the free edges in plastic and through the free edges and materials itself. Depending on the adhesive and the bonded materials, the shear strength change was confirmed. The average values of shear strength and calculated values necessary for assessing the effect of humidity, type of adhesive and type of materials on the shear strength are in Tab. 1 and Fig. 3. Humidity of dry environment WR = 45% corresponds to the moisture of PB w = 6.83%. The humidity of wet environment WR = 90% corresponds to the moisture of PB w = 17.03%.

Table 1. The average values of shear strength and calculated values necessary for assessing the effect of humidity, type of adhesive and type of materials on shear strength – the basic statistic characteristics

Type of adhesive	Relative Humidity	Glued material	Number of specimens	Average shear strength τ (MPa)	Coefficient of variation for τ
PUR Leim 507.0	WR=45%	plastic+plastic	19	2.89	16.02
		plastic+PB	12	0.825	14.80
		PB+PB	14	0.485	22.09
	WR=90%	plastic+plastic	19	3.33	10.94
		plastic+PB	7	0.72	23.87
		PB+PB	18	0.53	14.17
CHS-EPOXY 371	WR=45%	plastic+plastic	25	2.15	8.80
		plastic+PB	18	1.70	6.83
		PB+PB	16	0.392	13.92
	WR=90%	plastic+plastic	16	2.225	6.73
		plastic+PB	13	0.888	8.89
		PB+PB	11	0.448	6.76

Both types of adhesives can be described in similar way - the highest values of shear strength are shown using plastic-plastic joints, the lowest values of shear strength result from using PB-PB joints. The same maximum amount of glue was applied in order to gain results comparable using all material combinations. Decrease in shear strength in PB-PB glued joints can be explained by the fact that PB as a porous material saturates a part of the adhesive, thereby, the thickness of the glue line reduces.

Following the significance test for shear strength (Tab. 2) we can see that humididity itself does not affect shear strength. However, the significant influence of moisture is observed in interaction with the material and the type of adhesive. In any cases, it was confirmed that it is an important conclusion that humidity is not only affecting the performance of the adherent wood significantly but also adhesives typically used in wood bonding (KONNERTH *et al*. 2006).

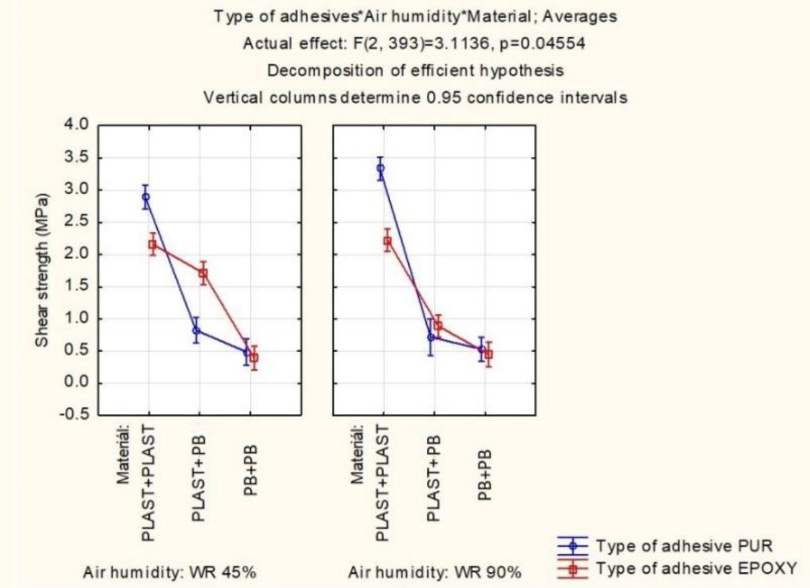

Fig. 3 Comparison of the shear strength of joints for different adhesives, humidity and glued material.

Tab. 2 Data of significance test for shear strength – analysis of variance.

Effect	SQ	Degrees of freedom	QM	F – value	P – value
Type of adhesive	2.4222	1	2.4222	7.749	0.005634
Relative humidity WR	0.2668	1	0.2668	0.853	0.356141
Material	363.1831	2	181.5916	580.934	0.000000
Type of adhesive* Relative humidity WR	3.0662	1	3.0662	9.809	0.001866
Type of adhesive* Material	33.6144	2	16.8072	53.768	0.000000
Relative humidity WR* Material	8.1707	2	4.0854	13.070	0.000003
Type of adhesive* Relative humidity WR* Material	1.9456	2	0.9733	3.114	0.045540
Error	122.8462	393	0.3126		

Because of the different number of specimens in each test set we used the HSD post hoc test to determine significant impact of humidity, adhesive and material (Tab. 3).

Tab. 3 HSD post hoc test.

No.	Type of adh.	WR (%)	Material	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}
1	PUR	45	PL+PL	-	0.000018	0.000018	0.037260	0.000018	0.000018	0.000019	0.000018	0.000018	0.000044	0.000018	0.000018
2		45	PL+PB	0.000018	-	0.469061	0.000018	0.999996	0.689325	0.000018	0.000018	0.123940	0.000018	0.999999	0.297779
3		45	PB+PB	0.000018	0.469061	-	0.000018	0.992972	1.000000	0.000018	0.000018	0.999970	0.000018	0.205341	1.000000
4		90	PL+PL	0.037260	0.000018	0.000018	-	0.000018	0.000018	0.000018	0.000018	0.000018	0.000018	0.000018	0.000018
5		90	PL+PB	0.000018	0.999996	0.992972	0.000018	-	0.998946	0.000018	0.000018	0.910343	0.000018	0.999580	0.976209
6		90	PB+PL	0.000018	0.689325	1.000000	0.000018	0.998946	-	0.000018	0.000018	0.997267	0.000018	0.256868	0.999981
7	EPOXY	45	PL+PL	0.000019	0.000018	0.000018	0.000018	0.000018	0.000018	-	0.017212	0.000018	0.999996	0.000018	0.000018
8		45	PL+PB	0.000018	0.000018	0.000018	0.000018	0.000018	0.000018	0.017212	-	0.000018	0.002772	0.000018	0.000018
9		45	PB+PL	0.000018	0.123940	0.999970	0.000018	0.910343	0.997267	0.000018	0.000018	-	0.000018	0.010995	1.000000
10		90	PL+PL	0.000044	0.000018	0.000018	0.000018	0.000018	0.000018	0.999996	0.002772	0.000018	-	0.000018	0.000018
11		90	PL+PB	0.000018	0.999999	0.205341	0.000018	0.999580	0.256868	0.000018	0.000018	0.010995	0.000018	-	0.052966
12		90	PB+PL	0.000018	0.297779	1.000000	0.000018	0.976209	0.999982	0.000018	0.000018	1.000000	0.000018	0.052966	-

The highest values of shear strength were achieved by bonding two plastic elements using PUR adhesive. The increase in strength of 12.13% occurred when the humidity increased. It is considered statistically significant difference. It is due to the fact that moisture remains on the surface of the test specimen after conditioning of the plastic material which resulted in better hardening of PUR adhesive and creating the stronger joint. In the glued joint consisting of two PB elements, the shear strength increased by 9.5% when the humidity increased as well. This is not statistically significant at a given number of test specimens. This lesser increase in shear strength compared to plastic joints can be caused by the fact that moisture on the PB surface is not so concentrated and it is evenly distributed over the thickness of the PB. Due to the increase in moisture the shear strength decreased by 13% when different materials were glued together, PB and plastic material. However, this value is not statistically significant at a given number of specimens. These specimens were damaged by adhesive failure (AF) in the glue line (Fig. 5a). One of the adherents (PB) was damaged using the PB + plastic specimens at the humidity of 45%. Folowing the findings it is clear that PUR adhesive is not suitable for bonding different materials (PB+Plastic) at increasing humidity.

Epoxy adhesive is the most suitable for bonding composites, i.e. bonding different materials. This assumption was confirmed by the tests. The highest value of shear strength of 1.70 MPa with epoxy adhesive was achieved during the bonding of PB and plastic. However, when humidity increased, there was a statistically significant decrease in shear strength by 48.3%. This change was observed in the failure in the glue line (Fig. 5) when cohesive damage to the glued joint occurred. Compared to the polyurethane adhesive when humidity increased and the material combination of PB-plastic was used, the shear strength of epoxy adhesive increased by 19%. The impact of the increase in humidity when same materials are bonded together (plastic + plastic, PB + PB) is statistically insignificant. The damage to glued joints at different humidity is shown in Fig. 4 and 5.

a) b)

Fig. 4 Damage to glued joint using plastic + PB at the humidity WR 45% a) PUR adhesive , b) epoxy adhesive

a) b)

Fig. 5 Damage to glued joint using plastic + PB at the humidity WR 90% a) PUR adhesive , b) epoxy adhesive.

CONCLUSION

The study was focused on the impact of humidity on shear strength of glued joints and on the evaluation of the suitability of bonding the particle board and plastic material at increased humidity. In general, we can say that the influence of humidity on the shear strength of joints is not statistically significant. The experimental results and their analysis allow us to mention following conclusions:

– Following the results obtained, PUR adhesives that harden due to humidity are more suitable for bonding same materials in the wet as well as in dry environment.
– Epoxy adhesive is the most suitable for bonding different materials, in our case PB and plastic material.
– Tests were performed using specimens with lap joint. Forasmuch, investigated materials has significantly different properties; we can propose to verify the impact of humidity on scarf joint as well.

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