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Comparison of the bond strength of oak (*Quercus* L.) and beech (*Fagus sylvatica* L.) wood glued with different adhesives considering various hydrothermal exposures

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ABSTRACT: The investigation of the hydrothermal exposure effect on the glue-line strength is obvious when outdoor application of wood products is in option. In our research the bonding quality of oak (*Quercus* L.) and beech (*Fagus sylvatica* L.) wood was tested in different conditions according to EN 205. After each exposure the lap joint test specified the shear strength of wood bonded with PVAC and PU adhesive. In our research different behaviour concerning both types of adhesives and selected wood species was observed. The most significant decrease (–80%) of the shear strength was found when the PVAC was used to bond oak wood. Therefore the PVAC adhesive is most likely less suitable for the bonding of the block board in outdoor conditions. On the contrary, the best results in the same conditions were obtained by the oak when the polyurethane adhesive was used. It indicates that the PU adhesive is more suitable for the bonding of oak wood. Considering results of beech wood, there were not found this interaction.

Keywords: adhesion of wood; hydrothermal exposure; oak; beech

The popularity of laminated products is on the rise considering various indoor and outdoor applications. Wood as a raw material which is used in laminated compositions brings many advantages to the products such as dimensional stability, sustainability or aesthetic appeal. Adhesives play an important role for laminated compositions and their mechanical performance (Dilik et al. 2007). Therefore it is vital to select proper adhesives and specify their mechanical performance in various conditions, including the combination of moisture and thermal exposure. Although there are many types of adhesives, the polyurethane and polyvinyl acetate adhesive is a popular and widely used choice. Research dealing with these adhesives was conducted, using directly the traditional procedure of lap joint testing without any treatment (Konnerth et al. 2006). From the pertinent literature there are known cases where temperature change (Clauss et al. 2011) or moisture change (Minelga et al. 2013) was a part of the testing variables. Of course, there are other effects which take part in the mechanical behaviour such as penetration depth (Hass et al. 2012; Mendoza et al. 2012) or surface roughness of wood (Follrich et al. 2010) followed by the effect of various wood species (Schmidt 2010; Aicher, Ohnesorge 2011). We have taken into account these facts and designed a research where two species, oak and beech, bonded with two common adhesives, are of major interest. Since single-environment exposure was part of many research surveys, we suggest performing tests in different hydrothermal conditions according to EN 204 and standard lap joint test complying with EN 205. From the results obtained on beech (*Fagus sylvatica* L.) and oak (*Quercus* L.) wood samples we want to provide sufficient information for instance for the wood building industry. Our research resulted in the following hypothesis: (1) if the hydrothermal exposure is employed, then the bonding properties of

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wood species are different; (2) if different wood species are glued, then different behaviour in relation to the type of adhesives is produced.

MATERIALS AND METHODS

In our research the bonded boards were prepared from beech (*Fagus sylvatica* L.) and oak (*Quercus* L.) wood panels. The panels were produced from the wood with moisture content 12%. The surfaces of the wood were sanded before bonding with sandpaper of 100 grit roughness (P100) to prepare the surface for the adhesive. Then two types of adhesives were used for the gluing of sandwich block-boards. The prepared wood of oak and beech was glued using polyvinyl acetate (PVAC) "Synurit F" and polyurethane "Kleiberit 201.6". The adhesives were manually applied onto the surfaces in an amount of 120 g·m^{-2}. Different conditions were used for the production of samples. Curing time and used specific pressure followed the recommendations of adhesive producers. Boards with PVAC adhesive were pressed by a specific pressure of 0.6 N·mm^{-2} for 25 min and boards bonded with PU adhesive were pressed by the same pressure for 7 h. After the panel assembly the panels were conditioned at 20°C and 65% relative humidity obtaining the moisture content of 10 ± 0.5% (EN 322). After conditioning the panels were tested in different conditions including the hydrothermal process following EN 204 standard and the samples were obtained from panels according to EN 205 (Table 1).

To obtain the shear strength of the bond line the samples were tested according to EN 205. From each type of panel 20 samples were obtained. By the tensile method the tensile shear strength was measured employing a universal testing machine ZWICK Z050 with TestXpert software where the rupture of the sample was obtained in 60 seconds. Consequently the data were assessed by STATISTICA v. 10 software. The basic descriptive statistics was carried out and the normal distribution of data was confirmed by the Shapiro-Wilk test. The ANOVA was employed to provide levels of significant differences between data sets and to obtain between-subjects effects the Scheffé post-hoc test was included. The results in the text are abbreviated according to wood species, environmental class number of hydrothermal exposure and type of adhesive, respectively.

Table 1. Environment exposures according to EN 204

Environment class	Water 20°C	Water 100°C	Conditioning 20°C; 65% RH (days)
1	–	–	7
2	4 days	–	7
3	2 h	6 h	7

Table 2. Descriptive statistics of the bonded samples

Type	Shear strength (N·mm^{-2})			
	mean	min	max	SD
OAK1/PU[v]	12.31	10.19	13.61	1.09
OAK1/PVAC	12	9.96	13.76	1.04
BE1/PU[v]	11.63	8.86	14.3	1.49
BE1/PVAC	10.53	8.38	12.13	1.18
OAK2/PU*[w]	4.78	2.9	6.24	0.87
OAK2/PVAC*	2.44	2	2.95	0.28
BE2/PU*[w]	3.95	3.15	4.49	0.45
BE2/PVAC*	3.82	3	5.19	0.65
OAK3/PU*[w]	4.09	2.9	6.69	0.8
OAK3/PVAC*	1.95	1.55	2.7	0.27
BE3/PU*[x]	2.74	1.5	3.85	0.61
BE3/PVAC*[x]	2.71	2	3.25	0.33

*significant at 0.05 (ANOVA), [v, w, x] the same letters indicate not significantly different (Scheffé post-hoc test)

RESULTS

Environment type 1 (20°C, 65% relative humidity for 7 days)

In the first class of the environment the samples are considered as control samples since the conditioning for 7 days is employed. With regard to obtained results, the species provided different results of shear strength (Table 2). The best performance was shown by oak bonded with PU adhesive (OAK1/PU) with the shear strength of 12 N·mm^{-2}, the beech wood (BE1/PU) performed on the same strength level, since no statistical difference was found (ANOVA, $P < 0.05$). Considering samples bonded with PVAC, the higher shear strength was shown by bonded oak wood (OAK1/PVAC) compared to the beech wood (BE1/PVAC). The shear strength of BE1/PVAC was lower by 12% (ANOVA, $P < 0.05$).

Environment type 2 (20°C water for 4 days and 20°C, 65% relative humidity for 7 days)

In the 2nd class where the samples were exposed to water for 4 days and conditioned afterwards, the best performance was shown by oak wood bonded with PU (OAK2/PU) and beech bonded with PU (BE2/PU) while there was found no difference (ANOVA, $P < 0.05$). The shear strength reached the values near to 5 N·mm^{-2}. Using PVAC adhesive, the shear strength of oak (OAK2/PVAC) was signifi-

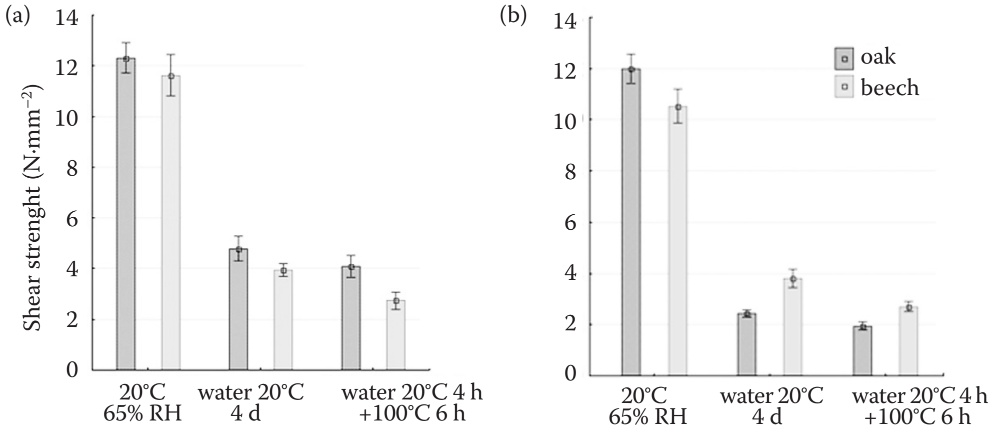

Fig. 1. Shear strength of the samples bonded with (a) PU, (b) PVAC

cantly lower (–36%) than the shear strength of the PVAC bonded beech wood (BE2/PVAC).

Environment type 3 (20°C water for 2 h, 100°C water for 6 h and 20°C, 65% relative humidity for 7 days)

In the third class the samples were exposed to the combination of boiling water and cold water, which provided the last aggressive environment where the samples were placed. The best shear strength performance in this class was indicated by oak bonded with polyurethane adhesive (BE3/PU), where the value of 4.09 $N\cdot mm^{-2}$ was reported. This mechanical performance was followed by the oak bonded with PU (OAK3/PU) and beech bonded with PVAC (BE3/PVAC), when the same values of shear strength, near to the 2.7 $N\cdot mm^{-2}$ (ANOVA; $P < 0.05$), were measured. The lowest value of 1.95 $N\cdot mm^{-2}$ was obtained for oak wood bonded with PVAC adhesive (OAK3/PVAC).

All results are presented in Table 2 as descriptive statistics where the mean value (mean), minimal value (min), maximal value (max) and standard deviation (SD) are shown.

Considering the PU adhesive, different behaviour of the two wood species was found out. When using the PU adhesive, no significant difference in shear strength (ANOVA, $P < 0.05$) was revealed between the first two environment exposures. OAK1/PU and BE1/PU reached the same values around 12 $N\cdot mm^{-2}$. The 2nd environment class indicates the same decrease of the shear strength properties to the value around 4 $N\cdot mm^{-2}$. Surprisingly, in the 3rd environment class it was indicated that the PU is more suitable to bond oak wood since the shear strength of oak wood (OAK3/PU) was by 33% higher than in bonded beech wood (BE3/PU) (ANOVA, $P < 0.05$). Moreover, OAK2/PU performed indifferently to OAK2/PU and BE2/PU (ANOVA, $P < 0.05$), which makes the oak wood much more suitable for bonding with PU adhesive than the beech wood. Data are summarized in Fig. 1.

On the contrary, different behaviour of PVAC adhesive was found in relation to different wood species. In the 1st environment class the shear strength of oak wood (OAK1/PVAC) showed a significantly higher shear strength than beech wood (BE1/PVAC) by 12%. Nevertheless, the behaviour of wood species in the second and third environment class showed an opposite trend. In the 2nd class the shear strength of the oak wood bonded with PVAC (OAK2/PVAC) was significantly lower by 56% than in the bonded beech wood (BE2/PVAC) and in the 3rd class the shear strength of the bonded oak wood (OAK3/PVAC) was lower by 39% than in the bonded beech wood (BE3/PVAC). With regard to the results the PVAC adhesive applied to oak wood is more prone to the weakening with changed moisture conditions. The results are summarized in a box-and-whisker plot in Fig. 1.

DISCUSSION

In our research we successfully presented the tensile shear strength of different adhesives in three types of environment. We assume that the reported decrease of shear strength may be caused by various factors or their combinations. Firstly, the decreasing tendency concerning the type of used adhesive, especially when hot water was used, can be assigned to the thermoplastic origin and possible chemical constitution of the adhesive backbone (Frihart 2009). Furthermore, the overall decrease of the shear strength performance along the changed environment (EN 204) can probably be caused also by softening behaviour in the cohesive zone of the bonding agent (Custódio et al. 2009) and hydrothermal stresses such as swelling and shrinkage occurring in adjoining wooden layers (Kläusler et al. 2014). An interesting behaviour was shown by PUR adhesives when in each of the environments PUR bonds had shown a higher shear strength performance. These findings complied with previously reported studies (Uysal, Özçifçi 2006; Clauss et al. 2011; Brandmair et al. 2012). This difference may be related to a different curing process of the solvent, as the cross-linking mechanism in PVAC glue is not employed. Moreover, an interesting behaviour concerning the wood species was observed. The PUR adhesive was found to be more suitable for the bonding of oak wood since this bonding has shown overall higher shear strength characteristics than PVAC bonding. A different behaviour was observed in the bonding of beech wood where differences between PUR and PVAC were not so significant. This phenomenon can be caused by different porous structure (Plötze, Niemz 2010) of the assessed wood species.

CONCLUSION

In our research we successfully reported the tensile shear strength of PU and PVAC adhesives applied in the bonding of beech and oak wood. In summary, both our hypotheses were confirmed. Firstly, the bonding properties are significantly altered by different hydrothermal exposure. Secondly, the wood species were proved to have a significant effect on the shear strength property. Different performance was the most obvious when specimens were exposed to hydrothermal environment. Especially then the same adhesives showed different performance of wood species. To sum up, this research successfully assessed the tensile shear strength of different adhesives in a way that is necessary for the preparation of wood block boards used in the building industry. We assume that our assessment may be a significant contribution in this branch.

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