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# Adhesive bond performance of heat-treated wood at various conditions

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## Abstract

Heat treatment of wood leads to chemical, structural and physical changes in wood constituents, which can significantly affect the bonding performance of wood in several ways depending on the adhesive type used. In the present study, fir (*Abies bornmülleriana* Mattf.) and beech (*Fagus orientalis* L.) were heat treated at 170 ºC, 180 ºC, 190 ºC, 200 and 212 ºC for 2 hours. Four different types of adhesives were used for bonding process: melamine-urea-formaldehyde (MUF), melamine formaldehyde (MF), phenol formaldehyde (PF), and polyurethane (PUR). For all the pretreatment conditions, highest shear strength of adhesive bonds of each adhesive system was observed for untreated samples and shear strength decreased with increasing heat treatment. The strength of each adhesive bond of samples which were soaked in water was much less than dry samples, approximately half of the dry strength. Generally, the shear strength of the adhesive bonds after boiling was smaller than or similar to the values obtained for soaking. The untreated samples lost more strength after soaking and boiling than heat treated samples. With increasing heat treatment severity, reduction in shear strength increased in dry samples while decreased in soaking and boiling samples. For instance, after soaking, the untreated samples lost more strength (almost 39%) than heat treated samples (almost 24% for most severely heat treated samples). The results showed that the shear strength of adhesive bonds was influenced by heat treatment and depended on pretreatment of samples prior to testing. In general, all adhesives used performed in quite a similar way for all pretreatment conditions, and the bonding performance of heat treated fir wood was less satisfactory than that of beech wood for all adhesive system and condition.

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## Introduction

Wood heat treatment has increased significantly in the last few years. In many applications, heat treated wood is joined with bonding agents. Bonding of heat treated wood with several adhesives would significantly extend the application areas (Sernek *et al.*, 2008).

Heat treatment of wood changes its chemical composition by degrading cell wall compounds and extractives. The chemical changes have been studied extensively by using different chemical analyzing methods such as elemental analysis (CHNO, CHN), UV spectroscopy, $^{13}$C Nuclear magnetic resonance (CPMAS, $^{13}$C-NMR) and Fourier transfer infrared (FTIR), XPS ( Wikberg and Maunu, 2004; Tjeerdsma and Militz, 2005; Nuopponen *et al.*, 2004; Boonstra and Tjeerdsma, 2006; Inari *et al.*, 2007; Dumarçay *et al.*, 2007; Mburu *et al.*, 2008; Kocaefe *et al.*, 2008; Gonza´lez-Pena *et al.*, 2009). Chemical changes due to heating depends on duration and temperature of the treatment, temperature being the main factor (Esteves and Peereira, 2009; Tjeerdsma *et al.*, 1998; Militz, 2002; Tjeerdsma and Militz, 2005). As a result of thermally induced chemical changes to wood components, the physical, mechanical and biological properties of wood are altered (Boonstra *et al.*, 2007; Syrjanen and Oy, 2001; Tjeerdsma *et al.*, 1998; Bekhta and Niemz, 2003).

Heat treatment of wood can affect the bonding process in several ways depending on the types of adhesive used (Boonstra *et al*., 1998; Sernek *et al*., 2008; Sahin Kol *et al*., 2009; Adamopoulos *et al*., 2012). Strong adhesion between adhesive and wood is achieved by appropriate adhesive flow, penetration, wetting and curing (Marra, 1992). It has been found that dimensional characteristics of wood are generally improved as a result of heat treatment. Reduction in free hydroxyl groups decreases moisture uptake, and is additionally accompanied by the formation of hydrophobic substances due to cross-linking reactions of wood polymers (Ohlmeyer, 2007). Due to less hygroscopic character of heat treated wood (Borrega and Karenlampi, 2007; Tjeerdsma and Militz, 2005) both distribution of adhesive on wood surface, as well as, penetration of adhesive into porous wood structure can be affected, because most wood adhesives contain a large amount of water as solvent (Sernek *et al*., 2008; Kariz and Sernek, 2010). The wettability of heat treated wood decreases and studies by 13 C CPMAS NMR and FTIR analysis suggested that the reasons for decrease in wettability could be a modification of the conformational arrangement of wood biopolymers resulting from the loss of residual water or, more probably, from the plasticization of lignin and increase in cellulose crystallinity (Hakkou *et al.*, 2005; Petrissans *et al*., 2003). The contact angle increased significantly as the treatment temperature was increased (Kocaefe *et al*., 2008). Decrease in wettability might hinder waterborne adhesives from adequately wetting the surface (Sernek *et al*., 2008). Low hygroscopicity of heat-treated wood might affect the curing of water- borne glues (Boonstra *et al*., 1998). Since heat treated wood absorbs moisture slowly (Esteves and Peereira, 2009), the open time for waterborne adhesives can be 6 times greater than used with untreated wood (Grøstad and Pedersen, 2010; Krystofiak *et al*., 2013). Adhesives can also over penetrate the porous wood structure because of limited capacity of heat treated wood tissue to absorb water from the curing adhesive bond line, so the adhesive stays mobile for a longer period of time (Kariz and Sernek, 2010). The pH value of wood is another factor which could affect the bonding process. Heat treatment results in decreased in pH, which probably affects the curing process depending on adhesive type used (Pizzi, 1983; Sernek *et al*., 2008).

The shear strength of heat treated wood decreased, and this can affect the shear strength of adhesive bond (Kariz and Sernek, 2010). Reduction in adhesion between fibres of the wood matrix will lead to premature failure of the bonded wood even if the adhesive line itself remains sound (Hill, 2006). Sometimes, it is difficult to determine whether the adhesive bond strength decreases because of poor bonding or due to reduced strength of heat-treated wood (Kariz and Sernek, 2010). Chow (1971) studied shear strength properties of PF-bonded veneers, finding that there was a reduction in bonding strength and a higher proportion of wood failure as temperature and treatment time increased. Chang and Keith (1978) bonded heat-treated wood specimens of aspen, beech, maple and elm with UF resin. There was a reduction in shear strength of glue line as both temperature and time of treatment increased, although aspen performed rather better than other woods tested. On the other hand, improved bonding performance can be achieved as the improved dimensional stability of heat treated wood results in less shrinking and swelling stress on the cured adhesive (Sernek *et al*., 2008; Boonstra *et al*., 1998; Kariz *et al*., 2013).

Variety of wood adhesives, species, and modification methods make bonding behavior of heat treated wood a complex subject. With heat treatment processes becoming commercially and increasing use of heat treated wood for exterior and interior applications, it is important to continuously update our knowledge on adhesive bonding of heat treated wood. In Turkey, Thermowood is becoming more popular nowadays and fir and beech are the main wood species for industrial-scale. In view of the above, the main objective of the study was to determine the adhesive bond performance and wood failure of heat treated fir and beech bonded with four common wood adhesives (phenol–formaldehyde, melamine–formaldehyde, melamine-urea-formaldehyde and polyurethane).

## Materials and Methods

Fir (*Abies bornmülleriana* Mattf.) and Oriental beech (*Fagus orientalis* L.) procured from a local saw mill were used in heat treatment study. 10 planks (30×200 mm in cross section and 3 m long) from each wood species were selected. The criteria for selection was cleanness of sapwood, small variation in the year ring width a good quality of sawn timber. The planks chosen were sawn and planed on four sides. Then, these 3 m long planks were split from middle and cut into 60 cm long pieces. The others halves of these 10 planks were left as reference material because the heat treated and untreated samples were from the same planks. The other halves of these planks were heat-treated under steam at five different temperatures (Fig. 1). Pre-dried wood samples contained 11-16% moisture content before heat treatment. Melamine-urea-formaldehyde (MUF), melamine formaldehyde (MF), phenol formaldehyde (PF) and polyurethane (PUR) adhesives were used for bonding. The ready-to-use adhesives were supplied from POLISAN, producer firms in Turkey (Table 1).

**Heat-treatment process (Thermo wood) :** Heat-treatment was carried out under accurate conditions under steam in laboratory kiln of Nova Thermo Wood Gerede, Turkey, at 170 °C, 180 °C, 190 °C, 200 °C and 212 °C. Time of thermal modification at the target temperature was 2 hrs in every test

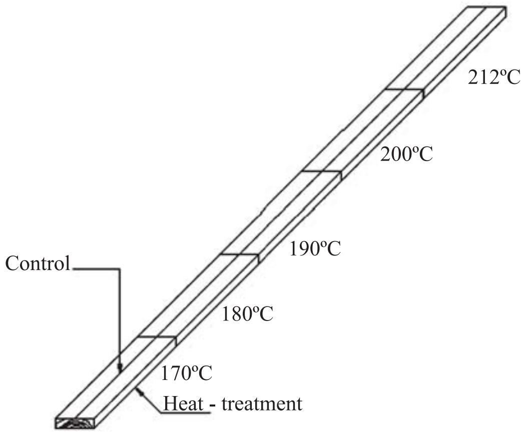


**Fig. 1 :** Descriptions of the wood materials used in tests

**Table 1 :** Adhesives

| Adhesives | Density (20 ºC) (g cm$^{-3}$) | pH (20 ºC) | Viscosity (20 ºC) (cPs) | Solid (2 hr, 120 ºC)(%) |
|---|---|---|---|---|
| MUF | 1.239 | 8.80 | 150 | 55.72 |
| MF | 1.245 | 9.21 | 60 | 55.2 |
| PF | 1.201 | 11.0 | 380 | 46.32 |
| PUR | 1.110 | 7.0 | 550 | 100 |

run. After heat-treatment phase, temperature was reduced to 80 °C to 90 °C using water spray system. Conditioning was carried out to moisten heat-treated wood and bring its moisture content to 4%–7%. After heat treatment, only planks that were free of defects were selected for further testing.

**Weight loss and pH determination :** Weight loss of the sample were determined on dry mass basis, after oven-drying at 103 ºC for 48 hrs. Untreated and heat-treated planks were then cut into lamellas and conditioned in a standard climate with 65% relative humidity at 20 ºC.

pH value was evaluated by using extraction method. 20 g of wood was ground into small particles and soaked in 160 g of distilled water for 24 hrs. The extract was filtered and analyzed with a pH meter.

**Sample preparation and property testing :** Prior to bonding, all the lamellas were planed in order to ensure a smooth and flat surface. Then the adhesive was applied at the rate of about 180-200 g m$^{-2}$ on a single bonding surface of the rows (single glue line) as recommended by the manufacturer. The adhesives were spread uniformly on the lamellas by manually hand brushing. The press pressure, temperature and duration were applied as 2 kg cm$^{-2}$, 120 ºC and 15 min. for PF, MF an MUF adhesives and 2 kg cm$^{-2}$, 22 ºC and 90 min for PUR, respectively. Bonded samples were conditioned for 7 days at standard climate (20±2 °C and 65±3 % RH) and then cut into samples. Configuration of test samples and method of loading the samples in tension are shown in Fig. 2. Moisture content of the samples from each adhesive group was determined by gravimetric method.

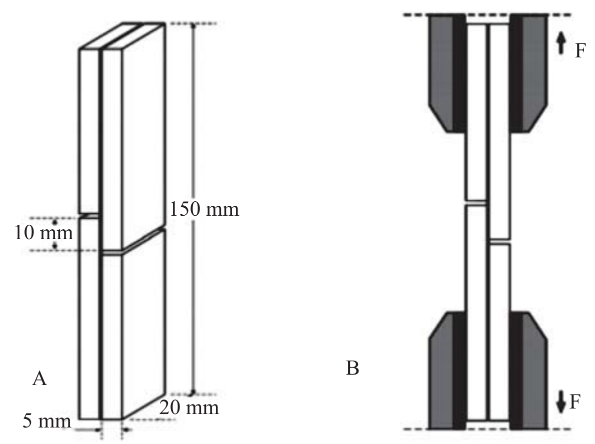


**Fig. 2 :** (A) Configuration of the test sample; (B) method of loading the sample in tension

Air-dry density of the samples was determined after calculation of air-dry volume and weight according to TS 2472 (1976). Samples from each adhesive group were divided into three sub-groups for different pretreatments, prior to testing according to TS EN 12765 (2004). The first group of samples (the dry samples) was tested in dry state after conditioning for 7 days in 65±5 % relative humidity 20±5 °C standard climate; the second subgroup of sample (pretreatment 1) was soaked in cold water (20 °C) for 24 hr; the third subgroup of samples (pretreatment 2) was boiled for 3 hr, cooled in water (20 °C) for 2 hr.

Shear strength tests were carried out in Zwick/Roel Z50 universal testing machine immediately after pretreatments according to BS EN 205 (2003). The loading speed was 5 mm min$^{-1}$. The loading was carried out until a break or separation occurred on the surface of test samples. Shear strength ($\sigma_k$) was calculated using the observed load ($F_{max}$) and bonding surface area of sample (A, mm$^2$) by the formula given below :

$$\sigma_k = \frac{F_{max}}{A} = \frac{F_{max}}{ab} \text{ (N.mm}^{-2}\text{)} \quad ....(1)$$

where, a is the width of glued surface (10 mm) and b is the length of glued surface (20 mm).

## Results and Discussion

The results indicated that heat treatment resulted in weight loss of wood, and the weight loss become more prominent if temperature of heat treatment increased (Table

2). Considering all heat treatment temperatures, the weight loss of beech was much higher than that of fir. Weight loss is mainly due to degradation of hemicelluloses, which are the most thermal sensitive polymer of wood components (Bourgois and Guyonnet, 1988; Zaman *et al*., 2000; Sahin Kol, 2010). Hardwood contains a higher proportion of hemicelluloses than softwood and thus, is degraded more extensively (Zaman *et al*., 2000; Esteves *et al*., 2007). Also, heat treatment decreased both the density and EMC of the samples, reduction being related to temperature (Table 2).

EMC of heat treated wood is used as an indicator of change in hygroscopicity. Reduction in the amount of sites available for water sorption (mainly hydroxyl groups) that accompanies degradation of hemicelluloses has often been suggested as an explanation for reduced hygroscopicity (Bektha and Niemz, 2003; Borrega and Karenlampi, 2007; Sahin Kol, 2010). Also, heat treatment reduced the pH of wood to 6.3 for fir and 6.8 for beech. Low pH after heat treatment might neutralize the alkaline hardeners used for phenolic resins and hinder the adhesive hardening or accelerate the chemical reactions of acid catalyzed amino resins (Pizzi and Mittal, 2003).

After dry shear test, highest shear strength of adhesive bonds of each adhesive system was observed for untreated control samples. The lowest average shear strength was observed for most heat treated samples. For all adhesives groups, heat treated samples showed a decreasing trend in shear strength with increasing treatment temperature (Table 3). Reduction in the shear strength of heat treated beech was higher than that of fir. The effect was similar for all used adhesive. A similar decrease in shear strength of adhesive bond due to heat treatment, has been reported previously (Poncsak *et al*., 2007; Sernek *et al*., 2007; Sahin Kol *et al*., 2009; Kariz and Sernek, 2010; Kariz *et al*., 2013; Dilik and Hiziroglu, 2012, Todaro *et al.,* 2015).

After dry test, the percentage of wood failure was quite similar (100%-71%) to all the groups of dry samples, except for MF and PF which were bit lower, but still very high. These results indicated that the differences in shear

**Table 2:** Treatment temperature and corresponding moisture contents, density, pH and weight loss of the samples prior to bonding

| Wood Species | | Temperature of heat treatment (°C) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Control | 170 | 180 | 190 | 200 | 212 |
| Fir | Moisture content (%) | 11.8 | 9.3 | 8.2 | 7.2 | 6.5 | 6.0 |
| | Density (kg $m^{-3}$) | 464 | 455 | 447 | 446 | 444 | 439 |
| | pH | 7.4 | 7.3 | 7.2 | 7.0 | 6.9 | 6.3 |
| | Weight loss (%) | - | 1.7 | 1.8 | 2.5 | 2.8 | 5.4 |
| Beech | Moisture content (%) | 12.4 | 9.8 | 8.5 | 7.3 | 6.4 | 5.8 |
| | Density (kg $m^{-3}$) | 659 | 644 | 639 | 639 | 625 | 617 |
| | pH | 7.1 | 7.0 | 7.0 | 6.9 | 6.9 | 6.8 |
| | Weight loss (%) | - | 1.2 | 2.6 | 3.3 | 3.9 | 7.3 |

**Table 3 :** Shear strength and wood failure of dry samples

| Wood species | Adhesive | | Temperature of heat treatment (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Control | 170 | 180 | 190 | 200 | 212 |
| Fir | MUF | Shear strength (N $mm^{-2}$) | 6.50 | 5.96 | 5.76 | 5.45 | 5.41 | 4.22 |
| | | Wood failure (%) | 100 | 100 | 100 | 100 | 100 | 100 |
| | MF | Shear strength (N $mm^{-2}$) | 7.79 | 6.97 | 8.11 | 6.38 | 7.23 | 4.95 |
| | | Wood failure (%) | 98 | 83 | 90 | 90 | 88 | 81 |
| | PF | Shear strength (N $mm^{-2}$) | 6.60 | 6.41 | 6.54 | 5.77 | 6.15 | 5.61 |
| | | Wood failure (%) | 78 | 86 | 84 | 78 | 74 | 72 |
| | PUR | Shear strength (N $mm^{-2}$) | 8.73 | 6.46 | 8.22 | 8.76 | 9.56 | 5.13 |
| | | Wood failure (%) | 100 | 100 | 100 | 100 | 100 | 100 |
| Beech | MUF | Shear strength (N $mm^{-2}$) | 18.27 | 11.89 | 9.53 | 8.19 | 7.67 | 5.35 |
| | | Wood failure (%) | 100 | 100 | 95 | 98 | 97 | 98 |
| | MF | Shear strength (N $mm^{-2}$) | 19.65 | 13.32 | 9.50 | 9.5 | 7.77 | 4.80 |
| | | Wood failure (%) | 100 | 82 | 85 | 90 | 85 | 88 |
| | PF | Shear strength (N $mm^{-2}$) | 14.33 | 9.13 | 9.98 | 10.65 | 7.68 | 5.11 |
| | | Wood failure (%) | 74 | 83 | 82 | 74 | 75 | 71 |
| | PUR | Shear strength (N $mm^{-2}$) | 19.19 | 16.59 | 11.87 | 15.27 | 12.26 | 4.98 |
| | | Wood failure (%) | 100 | 100 | 98 | 96 | 98 | 97 |

strength between the wood species tested were inherent shear strength of each wood species (Bakar *et al*., 2013). Heat treatment decreased the shear strength of wood itself, because the percentage of wood failure was high after dry test. The results showed that the heat treatment resulted in weight loss of wood and the recorded weight loss for beech was higher than that of fir (Table 2).

Untreated wood appears to perform better than heat treated wood. In general, under dry condition, the bonding performance of PUR adhesive was more satisfactory that of similar heat treated wood with other used adhesives. For waterborne MUF, MF and PF adhesives, the shear strength of samples decreased after heat treatment especially, the most heat treated samples. Low EMC and pH of heat treated samples (Table 2) are thought to be the reason of this difference. A low MC of samples less hygroscopic affects the bonding process especially of waterborne adhesives. The intensity of water absorption from waterborne adhesives could affect the hardening process and subsequently the quality of adhesive bond (Sernek *et al*., 2008). Also, low pH of heat treated samples might affect the bonding process because low pH could accelerate the chemical reactions of acid catalyzed amino resins like melamine formaldehyde. On the other hand, a low pH of wood surface might neutralize the alkaline hardeners used for phenol-formaldehyde resins and hinder adhesive hardening (Pizzi,1983; Sernek *et al*., 2008). In most case, PU adhesive, which is not a waterborne adhesive, performed similarly (especially for most heat treated samples) and better than other tested adhesives. PUR adhesive required moisture for hardening processes. Low MC of most heat treated samples might affect the bonding performance of PU adhesive.

In terms of performance requirements for bonded samples after dry condition (according to TS EN 12765 standard), the shear strength of glue line must be at least 10 N $mm^{-2}$. With respect to the requirements, all groups of fir

**Table 4:** Shear strength, wood failure and reduction of the shear strength of samples as compared to dry samples after 24 hrs soaking in cold water

| Wood species | Adhesive | | Temperature of heat treatment (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Control | 170 | 180 | 190 | 200 | 212 |
| Fir | MUF | Shear strength (N $mm^{-2}$) | 4.89 | 4.46 | 4.15 | 4.17 | 4.10 | 3.96 |
| | | Wood failure (%) | 100 | 98 | 100 | 100 | 100 | 98 |
| | | Reduction of shear strength (compared to dry samples) (%) | 25 | 25 | 28 | 23 | 24 | 6 |
| | MF | Shear strength (N $mm^{-2}$) | 3.73 | 4.46 | 3.29 | 3.84 | 3.79 | 2.46 |
| | | Wood failure (%) | 79 | 68 | 56 | 64 | 58 | 67 |
| | | Reduction of shear strength (compared to dry samples) (%) | 52 | 36 | 59 | 40 | 48 | 50 |
| | PF | Shear strength (N $mm^{-2}$) | 5.09 | 5.38 | 4.95 | 4.46 | 4.82 | 3.74 |
| | | Wood failure (%) | 86 | 72 | 58 | 68 | 85 | 80 |
| | | Reduction of shear strength (compared to dry samples) (%) | 23 | 16 | 24 | 23 | 22 | 33 |
| | PUR | Shear strength (N $mm^{-2}$) | 4.17 | 5.07 | 4.80 | 3.22 | 3.64 | 3.18 |
| | | Wood failure (%) | 70 | 90 | 82 | 85 | 87 | 88 |
| | | Reduction of shear strength (compared to dry samples) (%) | 52 | 22 | 42 | 63 | 62 | 38 |
| Beech | MUF | Shear strength (N $mm^{-2}$) | 13.77 | 7.20 | 7.33 | 8.58 | 5.42 | 4.73 |
| | | Wood failure (%) | 100 | 95 | 98 | 97 | 95 | 97 |
| | | Reduction of shear strength (compared to dry samples) (%) | 25 | 39 | 23 | -5 | 29 | 12 |
| | MF | Shear strength (N $mm^{-2}$) | 6.22 | 8.83 | 8.88 | 8.89 | 5.03 | 3.94 |
| | | Wood failure (%) | 84 | 80 | 84 | 75 | 56 | 64 |
| | | Reduction of shear strength (compared to dry samples) (%) | 68 | 34 | 7 | 6 | 35 | 18 |
| | PF | Shear strength (N $mm^{-2}$) | 11.11 | 5.38 | 8.73 | 9.16 | 6.40 | 4.16 |
| | | Wood failure (%) | 80 | 71 | 76 | 74 | 66 | 62 |
| | | Reduction of shear strength (compared to dry samples) (%) | 22 | 41 | 13 | 14 | 17 | 19 |
| | PUR | Shear strength (N $mm^{-2}$) | 10.19 | 8.97 | 8.77 | 10.00 | 10.62 | 4.13 |
| | | Wood failure (%) | 68 | 88 | 85 | 88 | 74 | 76 |
| | | Reduction of shear strength (compared to dry samples) (%) | 47 | 46 | 26 | 35 | 13 | 17 |

samples showed shear strength of less than 10 N $mm^{-2}$. This means that untreated beech bonded with MUF, MF, PF, PUR and beech heat treated at 170 ºC and bonded with MUF, MF and PUR fulfilled the requirements, whereas the others did not.

Shear strength of each adhesive bond of the samples which were soaked in water for 24 hr was much less than that corresponding to dry samples (Table 4). This strength decreased approximately to half of the dry strength, but there were differences between different groups of specimens. After soaking in water, the shear strength of adhesive bonds decreased with increasing temperature of heat treatment of wood. On the other hand, control samples lost more strength after soaking than heat treated specimens. Reduction in shear strength decreased with increasing heat treatment temperature, especially most heat treated samples. This could suggest the positive effect of lower water absorption and better dimensional stability in heat treated wood on bond performance. These caused less damage to wood-adhesive bond due to less swelling.

For pretreatment 1, control groups had highest percentage of wood failure (100%-68%). All the heat treated samples exhibited a lower percentage of wood failure (especially samples bonded with MF and PF), which, in general, decreased with the severity of heat treatment. But the percentage of wood failure was still high and there was no significant difference between the adhesives. This indicated that, shear strength results were related to wood shear strength itself rather than to the adhesive bond. It is evident that soaking of samples in water decreased shear strength and percentage of wood failure of adhesive bond. A comparison between shear strength of each heat treated wood samples bonded with all adhesives showed that heat treated beech samples lost more strength after soaking than fir samples. For instance, the beech group of samples which were soaked in water lost almost 60 % of its shear strength with increasing

**Table 5 :** Shear strength, wood failure and reduction of shear strength of samples as compared to dry samples after 3 hrs boiling and 2 hrs cooling in cold water

| Wood species | Adhesive | | Temperature of heat treatment (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Control | 170 | 180 | 190 | 200 | 212 |
| Fir | MUF | Shear strength (N $mm^{-2}$) | 4.27 | 4.13 | 4.14 | 3.74 | 3.92 | 3.50 |
| | | Wood failure (%) | 99 | 92 | 96 | 94 | 83 | 78 |
| | | Reduction of shear strength (compared to dry samples) (%) | 34 | 31 | 28 | 31 | 28 | 17 |
| | MF | Shear strength (N $mm^{-2}$) | 4.70 | 3.97 | 4.10 | 3.54 | 4.12 | 2.88 |
| | | Wood failure (%) | 74 | 60 | 68 | 54 | 64 | 66 |
| | | Reduction of shear strength (compared to dry samples) (%) | 40 | 43 | 49 | 45 | 43 | 42 |
| | PF | Shear strength (N $mm^{-2}$) | 5.45 | 4.41 | 4.52 | 4.51 | 4.68 | 3.41 |
| | | Wood failure (%) | 74 | 60 | 68 | 54 | 44 | 36 |
| | | Reduction of shear strength (compared to dry samples) (%) | 17 | 31 | 31 | 22 | 24 | 39 |
| | PUR | Shear strength (N $mm^{-2}$) | 4.08 | 3.69 | 2.86 | 2.97 | 3.11 | 3.09 |
| | | Wood failure (%) | 70 | 62 | 68 | 50 | 54 | 42 |
| | | Reduction of shear strength (compared to dry samples) (%) | 53 | 43 | 65 | 66 | 67 | 40 |
| Beech | MUF | Shear strength (N $mm^{-2}$) | 9.65 | 3.81 | 3.69 | 5.05 | 4.12 | 4.03 |
| | | Wood failure (%) | 80 | 82 | 70 | 65 | 67 | 44 |
| | | Reduction of shear strength (compared to dry samples) (%) | 47 | 68 | 61 | 38 | 46 | 25 |
| | MF | Shear strength (N $mm^{-2}$) | 8.55 | 4.20 | 6.68 | 3.93 | 3.63 | 3.31 |
| | | Wood failure (%) | 66 | 48 | 72 | 50 | 56 | 62 |
| | | Reduction of shear strength (compared to dry samples) (%) | 56 | 68 | 30 | 59 | 53 | 31 |
| | PF | Shear strength (N $mm^{-2}$) | 6.50 | 5.46 | 7.80 | 4.11 | 4.14 | 3.27 |
| | | Wood failure (%) | 65 | 56 | 61 | 48 | 37 | 34 |
| | | Reduction of shear strength (compared to dry samples) (%) | 55 | 40 | 22 | 61 | 46 | 36 |
| | PUR | Shear strength (N $mm^{-2}$) | 7.67 | 4.01 | 5.81 | 3.29 | 3.16 | 3.08 |
| | | Wood failure (%) | 64 | 52 | 68 | 40 | 44 | 42 |
| | | Reduction of shear strength | 60 | 76 | 51 | 78 | 74 | 38 |

severity of heat treatment, whereas the most severely heat treated group of fir samples lost only 30%. This finding again indicated that decrease in shear strength was related to wood shear strength which decreased with increasing heat treatment temperature.

Among the four adhesives tested, MUF and PF adhesives exhibited lower reduction of shear strength of compared to dry samples after Pretreatment 1. In terms of performance requirements for bonded samples after pretreatment 1 (according to TS EN 12765 standard), the shear strength of glue line was 7 N $mm^{-2}$. This means that beech samples untreated and mild heat treated (170 ºC, 180 ºC and 190 ºC) and bonded with MUF, MF, PF and PUR fulfilled the requirements, whereas others did not.

Generally, the shear strength of adhesive bonds after pretreatment 2 was smaller than or similar to the values obtained for Pretreatment 1. Decrease in strength after boiling was more pronounced for beech samples (Table 5). Variation in shear strength between two wood species with increasing heat treatment temperature was more pronounced after pretreatment 2. This drop in shear strength was expected due to greater severity of pretreatment 2. The average shear strength of untreated and heat treated fir samples except for most severely heat treated samples was almost same for all the adhesive groups, whereas shear strength of untreated beech samples was significantly higher than that of heat treated samples. Shear strength of beech samples; however, were similar for all the groups of heat treated samples bonded with all adhesive system. Wood failure, as well as, shear strength decreased with increasing heat treatment temperature. For pretreatment 2, control groups had highest percentage of wood failure (99%-66%). All heat treated samples exhibited significantly lower percentage of wood failure (78%-36%) (especially samples heat treated at 212 ºC). This indicated that not only wood tissue but also wood adhesive interactions and cohesion of the adhesive developed during cure might be affected due to heat treatment (Kariz and Sernek, 2010).

Generally, the four adhesives used were structural wood adhesives with high performance for exterior use. A comparison between the behaviors of four adhesives used showed that the performance of all the adhesives used were relatively similar after pretreatment 2. In terms of performance, requirements for bonded samples after pretreatment 2 (according to TS EN 12765 standard), shear strength of glue line should be at least 4 N $mm^{-2}$. This means that all the untreated fir samples bonded with adhesive, and fir samples heat treated at 170 ºC, 180 ºC bonded with MUF, MF and PF fulfilled the requirement. For beech samples, all the untreated and heat treated at 170, 180 ºC samples bonded with all studied adhesives fulfilled the requirement. Also, beech samples heat treated at 190 and 200 ºC bonded with MUF and PF fulfilled the requirement.

The present study revealed that the shear strength of the adhesive bonds decreased by heat treatment and dependent on the pretreatment of samples prior to testing. The shear strength of adhesive bonds decreased by both soaking and boiling but the decrease that caused by boiling was a bit more than soaking. With increasing heat treatment severity, reduction in shear strength increased in dry samples while decreased in soaking and boiling samples.

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