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Effect of fungal infection on physico-mechanical resistance of WPC made from thermally treated wood/PP

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Abstract

The effect of fungal decay on the physico-mechanical characteristics of thermally treated wood flour-plastic composites was determined. Firstly, the wood chips (*Fagus orientalis* L.) were treated thermally for 30 and 120 minutes at various temperatures (120, 150, and 180 °C) under saturated vapour in a steaming vessel and they were ground by Wiley mill machine. Then, polypropylene, thermally treated wood flour, and MAPP as compatibilizer were used by melt compounding and injection molding process. Some physical and mechanical parameters were measured prior to and after fungal (*Trametes versicolor*) infection for 6 weeks. The flexural strength, flexural modulus, and impact strength of undecayed and decayed WPCs at 180 °C for 120 min and at 150 °C for 30 min increased, respectively, but the water uptake and thickness swelling of WPCs decreased at 180 °C for 120 min. The wood particles of WPCs treated at 180 °C for 120 minutes had the least mass loss. The mechanical property parameters were reduced after fungal infection. Moreover, the results showed that the moisture sorption and thickness swelling for all formulations of unrotted specimens were significantly lower than that of white-rotted specimens.

Keywords: Fungal decay, thermally treated wood, physical and mechanical properties, decay resistance, WPCs

Mantar enfeksiyonunun ısıl işlem görmüş odun/PP kompozitlerin fiziko-mekanik direncine etkisi

Öz

Mantar çürümesinin ısıl işlem görmüş odun unu-plastik kompozitlerin fiziko-mekanik özellikleri üzerindeki etkisi belirlendi. İlk olarak, odun talaşları (*Fagus orientalis* L.) buharlı bir kazanda doymuş buhar altında çeşitli sıcaklıklarda (120, 150 ve 180 °C) 30 ve 120 dakika termal işleme tabi tutulmuş ve Wiley değirmen makinesinde öğütülmüştür. Daha sonra polipropilen, ısıl işlem görmüş odun unu ve uyumlaştırıcı olarak MAPP eriyik birleştirme ve enjeksiyon kalıplama işlemi kullanılmıştır. Bazı fiziksel ve mekanik parametreler mantar (*Trametes versicolor*) enfeksiyonundan önce ve sonra 6 hafta boyunca ölçülmüştür. 180°C'de 120 dakika ve 150°C'de 30 dakika boyunca bozulmamış ve çürümüş WPC'lerin eğilme direnci, elastikiyet modülü ve darbe direnci sırasıyla arttı, ancak WPC'lerinsu alma ve kalınlığına şişmesi 180°C'de 120 dakika boyunca azaldı. 180 °C'de 120 dakika muamele edilen WPC'lerin ahşap parçacıkları en az kütle kaybına sahipti. Mekanik özellikler, mantar enfeksiyonundan sonra azaldı. Ayrıca sonuçlar, çürümemiş numunelerin tüm formülasyonları için su alma ve kalınlığına şişmesinin beyaz çürüklük numunelerden önemli ölçüde daha düşük olduğunu göstermiştir.

Anahtar kelimeler: Mantar çürümesi, ısıl işlem görmüş ahşap, fiziksel ve mekanik özellikler, çürüme direnci, OPK'lar

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1 Introduction

Wood as an important natural and renewable resource is available in large volumes at low cost with many excellent properties that have been used for many applications. In fact, the application of wood as raw and unprotected in many uses gives added value to final products. Usually, wood as a raw material for final consumer products possesses a number of properties that limits its application (Kozhin and Gorbachev, 2011). Wood as a lignocellulosic polymer absorbs the humidity easily and this phenomenon changes its characteristics and dimensional stability. It can cause bio-deterioration if the water absorption of wood does not protect (Oksman Niska and Sain, 2007; Clemons, 2008).

Heat treatment is an environmentally friendly wood modification method that has been widely used in the last decades to improve the properties of wood material and does not use harmful chemicals during the process (Poncsak et al. 2011; Jirouš-Rajković and Miklečić, 2019). Heat-treated wood has many applications for exterior applications such as decks, cladding, garden furniture, terraces, fences, doors, and windows as well as interior uses such as kitchen furniture, cabinets, decorative wall panels, parquet, sauna benches, and panels (Esteves and Pereira, 2009; Cui and Matsumura, 2019).

A polymer matrix forms the continuous phase surrounding the chemical component of wood in the wood-plastic composites (WPCs). These matrix polymers are typically low-cost commodity polymers which soften easily when they are heated that allow considerable forms when wood is combined with them. These synthetic materials absorb little moisture and they can be efficient barriers against moisture penetration by a well-designed composite (Oksman Niska and Sain, 2007; Clemons, 2008). Due to specific applications, wood composites need protection against the influences of moisture, climatic conditions, biological attack (rot, beetles, termites, marine animals) and fire (Gardner et al. 2003). Heat treatment as a technique is intended in order to improve the dimensional stability and durability of wood-based composites. Heat treatment of wood at conditions with low time and temperature can lead to protect the chemical composition of the wood cell wall polymers but there is need high temperature (more than the melting point of the holocellulose and lignin) to improve of the material ductility through strengthening. The resistance of grain boundaries to intergranular cracking and annealing is a necessary process to obtain a well-defined structure with superior mechanical properties (Hill, 2006). The mechanism that increases the rot resistance depends on the loss of the cellulose and hemicellulose in addition to the low moisture absorption of the cell wall. By reducing the hydroxyl groups from the wood cell wall structural components, the ability of enzymes to metabolize the substrate and/or the mode of action of low molecular weight diffusible reagents may be affected and reduced, also. It should be noted that the formation of biocidal chemicals is possible due to the heat treatment (Hill, 2006).

One of the effective thermal treatment methods that have been implemented by several researchers is hydrothermal treatment (Tjeerdsma and Militz, 2005; Endo et al. 2016). The time and temperature of treatment affect the efficiency of hydrothermal treatment (Saliman et al. 2017). Furthermore, the media of heating also plays an important role. Heat treatment of beech wood in acidic, neutraland alkaline buffered solutions was evaluated by Talaei and Karimi (2015) and they observed that treating of wood by using different buffered media can lead to changes in the mechanical properties.

The impact of different times and temperatures of heating in the air upon the durability of modified wood against *T. palustris* has been investigated (Kim et al. 1998). The relationship between the heating period and mass loss due to fungal rot was modelled using a

regression equation. As the heating period and temperature increased, the decay resistance was improved. It was predicted by numerical analysis that degradation resistance comparable to the absorption of 1% CCA treatment was obtained by applying heat for 150 hours at 150 ºC. Kamdem et al. (2000) also found that toxic by-products can be produced that can stop the growth of fungi due to thermal modification.

Based on the findings of Perçin (2022), all parameters of the air-dried density, equilibrium moisture content (EMC), surface roughness, bonding strengths of the black pine (*Pinus nigra* A.) and larch (*Larix deciduas*) woods decreased depending on the heat treatment conditions. The density and EMC values of the control specimens were higher than the heat-treated samples.

Arwinfar et al. (2016) and Hosseinihashemi et al. (2022) discuss the mechanical properties and long-term hygroscopic thickness swelling rate of heat-treated wood particle WPCs in different conditions; they found that the acceptable treatment to make the WPC was 150 °C for 30 minutes for mechanical strength; 120 °C for 30 min and 150 °C for 30 minutes for long-term hygroscopic thickness swelling rate. Moreover, the micromorphology images of the composites produced from the wood heated at the aforementioned conditions showed that there are considerably fewer pores and so broken fiber ends embedded in the matrix of polymer.

The water absorption kinetics of the heat-treated beech wood plastic composites were investigated by Hosseinihashemi et al. (2016). They observed that by increasing the intensity of the heating condition and soaking period, the water absorption decreased than the control composites. In addition, minimum water absorption was observed in composites with wood content that were heat treated at 180 °C for 120 minutes.

Lengowski et al. (2021) demonstrated that while there are significant chemical changes in wood material after heat treatment, hemicelluloses are the most affected compound. The effect of heat treatment on the shear strength of wood was assessed by Can et al. (2021). They reported that shear strength decreased significantly after heat treatment and that reduced chemical bonding or mechanical interlocking of adhesives, and the reduced strength of the brittle heat-treated wood might be responsible for the severity of conditions. Durmaz et al. (2019) measured the changes in the physical properties of the heat-treated wood, whereby the density and EMC declined with the increased treatment conditions. In a similar study, Bal (2015) reported that the density and EMC values of wood decreased after heat treatment. Decreases in EMC values depending on the heat treatment temperatures were also reported by Aytin et al. 2015.

In the literature, the physico-mechanical properties of the WPCs made from heat treated wood and non-wood materials were commonly evaluated. However, little information is available on the effect of fungal infection on the weight loss, water resistance, and bending and impact strengths of WPCs made from thermally treated wood. In addition, beech (*Fagus sylvatica* L.) wood is widely used in construction and building materials as well as wood-based composites industries. On the other hand, the use of thermal-treated wood material is increasing in the industries. So, it is important to determine the relationship between the fungal infection (*Trametes versicolor*) of the heat-treated wood material and physico-mechanical strength.

This study was aimed to analyse the effect of heat treatment on weight loss, water resistance, thickness swelling, flexural strength, flexural modulus, and impact strength parameters of WPCs made from beech (*Fagus orientalis* L.) wood.

2 Material and Method

2.1 Thermoplastic polymer, wood filler, and compatibilizer

Polypropylene V30S (PP) supplied by Petrochemical Company (Marun, Mahshahr, Iran) was used as the polymer matrix with a melt flow index of 16 g/10 min and a density of 0.87 g/cm^3. Oriental beech (*Fagus orientalis* L.) wood flour as lignocellulosic material which was milled by Wiley grinder was applied as reinforcement. PPG101, which is a maleic anhydride grafted polypropylene (MAPP), provided by Kimia Javid Sepahan Co. (Tehran, Iran) with a melt flow index of 64 g/10 min and density of 0.91 g/cm^3. The grafted maleic anhydride was used as the compatibilizer at a rate of 3% by weight in the composites.

2.2 Thermal treatment of wood chips

Prior to the processing of the composites, a drum-chipper was used for the chipping of beech logs. Wood chips were dried at room temperature for 24 h before the thermal treatment. Afterwards, the wood chips were heated and saturated by steam in a steaming vessel at different temperatures (120 °C, 150 °C, or 180 °C) for 30 or 120 minutes. Then, produced chips from the beech wood were milled into wood flour and oven-dried at 103 ± 2 °C for 24 h to reach 1% moisture content. The required materials were weighed and formulated according to Table 1.

Table 1. Untreated and modified composites (MC) preparation formulations

Treatment code	Beech wood flour (wt.%)	Polypropylene (wt.%)	MAPP* (wt.%)
A = Untreated composite	50	47	3
B = MC-30 min-120 ºC	50	47	3
C = MC-30 min-150 ºC	50	47	3
D = MC-30 min-180 ºC	50	47	3
E = MC-120 min-120 ºC	50	47	3
F = MC-120 min-150 ºC	50	47	3
G = MC-120 min-180 ºC	50	47	3

* MAPP = maleic anhydride grafted polypropylene.

2.3 Composites manufacturing

Intermeshing counter-rotating twin screw extruder (Model T20, 1990, Dr. Collin, GmbH, Germany) were used at a screw speed of 60 rpm for 14 minutes for the mixing of materials which barrel temperature gradient from 180 °C at six zone from feeding zones to the die zone. The extruded materials were cooled at laboratory conditions and then milled to produce suitable granules for further processing. For the milling of granules, a laboratory grinder (Wieser, WGLS 200/200 Model, Germany) was used and the milled granules were dried at 105 °C for 4 h in a laboratory oven. The injection molding machine (Model EM80, Aslanian Co., Iran) set at 160-180 °C temperature was also used for molding of test samples. In each molding operation, a complete set of samples (3 replicates) was produced for various tests. Finally, before the testing, the samples were conditioned at the temperature of 23 °C and relative humidity of 50% for at least 40 h according to ASTM D 618 (1999).

2.4 Fungus culture

The white-rot fungus (*T. versicolor*) was transferred to petri dishes containing malt extract agar (48 g/L) under laminar hood using sterile pincers. The plates were kept at 23 ºC for one week until the culture medium was fully covered by the mycelium of the fungus. The cultured fungus was transferred into petri dishes containing the culture medium and then incubated for one week at 23 ºC.

2.5 Inoculation of samples by Fungus

Inoculation of composite samples by the fungus was performed in the petri dishes. The dishes containing the fungus and the composite samples were incubated in an incubator for 6 weeks at 23 ºC and 75% RH. The sizes of control WPCs samples are shown in the Figure 1.

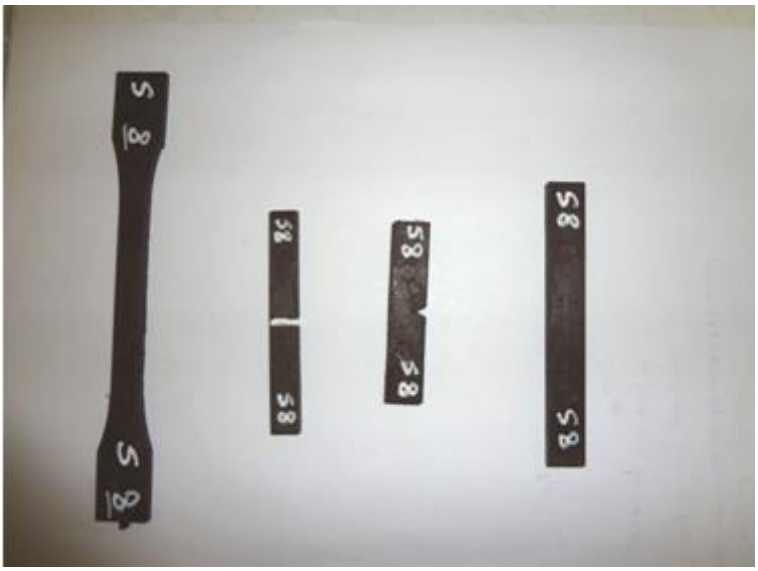

Figure 1. The sizes of WPCs control samples (The tensile test samples were not used in this study)

2.6 Mass loss

The dry mass of the samples was determined after 24 h under 103 ± 2 ºC. The mass losses were calculated using the Equation (1):

$$\text{Mass loss (\%)} = (Mb\text{-}Ma/Mb) \times 100 \quad (1)$$

where Mb and Ma are the oven-dry weights prior to and after inoculation with fungus, respectively.

2.7 Water uptake and dimensional stability tests

Water uptake and thickness swelling tests of the composites were conducted by following the ASTM D 570 (1998) standard. Five specimens from each formulation were selected and oven-dried for 24 h at 100 ± 3 °C. The samples were weighted with an accuracy of 0.001 g after drying in the oven and their thicknesses were measured at an accuracy of 0.001 mm. Then, the specimens were placed in distilled water for 24 h by the method of immersion and retained at room temperature (20 ± 2 ºC). In the final of this time, the excess on the surface of the specimen was cleared with a clean cloth and then their weights and thicknesses were determined. The water absorption values in percentage were calculated using the Equation (2):

$$WA(t) = \frac{W(t) - W_0}{W_0} \times 100 \quad (2)$$

where *WA (t)*, W_0, and *W (t)* denote the water absorption (%) at time t, the oven dried weight, and the weight of the specimen at a given immersion time t, respectively.

The thickness swelling values in percentage were calculated using Equation (3).

$$TS(t) = \frac{T(t) - T_0}{T_0} \times 100 \quad (3)$$

where *TS(t)*, T_0, and *T(t)* denote the thickness swelling (%) at time t, the initial thickness of specimens, and the thickness at time t.

2.8 Mechanical properties

The flexural properties (ASTM D 790-10 (2016)) and notched impact strength (ASTM D 256-10 (1997)) of WPCs made from thermally treated wood were determined according to ASTM standards.

2.9 Data analysis

Mass loss, flexural strength, flexural modulus, impact strength, water absorption, and thickness swelling values were evaluated using a computerized SPSS 17.0 statistical program and tested with ANOVA followed by Duncan's Multiple Range Test (DMRT) with 95% confidence level.

3 Results and discussion

3.1 Mass loss

Mass loss of the WPCs exposed to the white-rot fungus at different times and temperatures are shown in Table 2. According to the Table 2, when the time and temperature increase, it is clearly seen that the mass loss of the WPC specimens is decreasing, that is, the lowest mass loss was observed in the specimens formulated by thermally-treated wood at 180 °C for 120 minutes. According to the results of DMRT, the thermal treatment of wood had a significant effect on the mass loss of the WPCs. Among the composite formulations, the mass loss of the composites produced with thermally treated wood (30 min- 180 ºC, 120 min- 150 ºC, and 120 min- 180 ºC) have the highest durability (Table 2). The decay resistance of the modified beech wood by heating against the white decay fungus (*T. versicolor*) varied widely with the heat treatment conditions. Since white rot fungus can attack both lignin and cell wall polysaccharides (hemicelluloses and cellulose), the improved durability of the thermally treated beech flour can be attributed to the modification of its chemical components (Jimenez et al. 2011). Changes in the chemical composition of the wood due to heat treatment were correlated with increased resistance to fungal decay. While the hemicellulose content was dramatically reduced with increasing temperature and treatment duration, the lignin content increased proportionately (Yalcin and Sahin, 2015).

Reduced hemicellulose contents of the heated beech wood flour have a significant impact on biological resistance because it is an easily accessible carbon source for fungi (Nuopponen, 2005). The reduction in the amount of free -OH groups in the holocellulose and an increase in lignin cross-linking has caused a decrease in the equilibrium moisture which can also enhance the biological resistance of thermally treated wood (Wikberg and Maunu, 2004; Nuopponen, 2005). When wood is subjected to thermal treatment, formic and acetic

acids are formed. So, they cause the degradation of hemicellulose (Tjeerdsma et al. 1998). During hydrothermal modification, mass loss depends on the wood species, heating medium, temperature and duration (Esteves and Pereira, 2009). Theander and Nelson (1988) stated that the degradation rate of carbohydrates is high in acidic situations and is promoted by the high availability and low crystallinity of hemicelluloses. Further, variations in the acidity of the treatment media increase due to thermal treatment in wet environments because of the formation of acetic and formic acids on the basis of the decomposition of hemicellulose during hydrothermal modification in acidic media (Kubojima et al. 2000; Sulaiman et al. 2012). Lignin degradation occurred only when the treatment temperature was above 200 °C. Furthermore, the bending strength rapidly decreases at high temperatures (above 200 °C), treated wood shows darker colours and it becomes more brittle, and surface cracks are produced due to the further degradation of hemicellulose and the removal of -OH groups (Ali et al. 2021). Cross-linking was shown to reduce the amount of accessible OH groups that are simultaneously active in sorption which was explained based on the concept of sorption of water dimers at hydroxyl group pairs at high RH levels (Altgen et al. 2018).

Table 2. Mean value ± (standard deviation) for mass loss, flexural strength, flexural modulus, and impact strength of the untreated and modified composites

	Treatment code	Mass loss (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (J/m^{-1})
Undecayed	A = Untreated composite	-	63.77 a (6.46)	5129 ab (639.30)	6.94 cd (0.26)
	B = MC-30 min-120 ºC	-	72.52 bc (1.34)	5484 b (254.42)	5.93 a (0.48)
	C = MC-30 min-150 ºC	-	78.94 c (5.57)	5452 b (376.90)	6.08 ab (0.27)
	D = MC-30 min-180 ºC	-	73.92 bc (0.62)	5111 ab (265.90)	6.51 bc (0.21)
	E = MC-120 min-120 ºC	-	78.92 c (3.01)	5177 ab (372.01)	6.63 c (0.23)
	F = MC-120 min-150 ºC	-	74.72 bc (0.23)	5175 ab (202.95)	6.51 bc (0.22)
	G = MC-120 min-180 ºC	-	68.94 ab (3.62)	4559 a (147.87)	7.25 d (0.01)
Decayed	A = Untreated composite	0.22*ab (0.02)	61.63 a (0.92)	1779 b (41.87)	5.40 a (0.00)
	B = MC-30 min-120 ºC	0.32 bc (0.04)	70.09 bc (0.89)	1940 cd (21.08)	6.05 ab (0.29)
	C = MC-30 min-150 ºC	0.37 c (0.01)	76.64 d (2.93)	2001 d (79.62)	6.57 b (0.22)
	D = MC-30 min-180 ºC	0.16 a (0.01)	68.82 b (3.67)	1762 b (95.47)	5.30 a (0.22)
	E = MC-120 min-120 ºC	0.25 abc (0.14)	75.95 d (0.81)	1911 cd (4.16)	5.86 ab (0.47)
	F = MC-120 min-150 ºC	0.16 a (0.06)	73.02 cd (1.46)	1867 bc (69.93)	6.18 ab (0.91)
	G = MC-120 min-180 ºC	0.15 a (0.31)	68.82 b (1.71)	1640 a (67.82)	5.91 ab (0.47)

*Lower case letters on the numbers indicates the Duncan grouping of the averages. Values in parentheses are standard deviation (SD). Undecayed and decayed specimens were analyzed statistically and separately.

3.2 Flexural strength, flexural modulus, and impact strength

Statistical analysis of the data shows a significant effect on the mechanical strength of heat-treated wood flour of the undecayed and decayed WPCs. The results of Duncan's multiple range test indicated that the thermal treatment of wood had a significant effect on the mechanical properties of the undecayed and decayed WPCs. The undecayed and decayed WPCs produced from wood treated at 150 ºC for 30 min and 120 ºC for 120 min had the same flexural strength values and were higher than other treated WPCs (Table 2). All the undecayed and decayed WPCs showed higher flexural strength than the control WPC. Thermal-treatment of wood improved the flexural strength to a greater degree than the flexural modulus. The flexural modulus of the undecayed and decayed WPCs produced with wood treated at 120 ºC or 150 ºC for 30 min were considerably higher than that of the other treated WPCs and control WPC. The treatments 30 min at 180 ºC, 120 min at 120 ºC, and 120 min at 150 ºC did not have a significant difference in the flexural modulus of undecayed WPCs as compared to the undecayed control but the treatments 30 min at 180 ºC and 120 min at 150 ºC did not have significant difference in the flexural modulus of decayed WPCs as compared to the decayed control. The undecayed and decayed WPCs produced from wood treated at 180 ºC for 30 min or 120 min had lower flexural modulus than the undecayed and decayed control WPC. This result showed that the flexural properties of the undecayed and decayed WPCs considerably decreased as the thermal-treatment duration increased from 30 min to 120 min. In general, all the undecayed WPCs showed higher flexural strength than the decayed WPCs made from untreated and treated wood. The significant differences ($p<0.05$) between some group averages for the mechanical properties are shown in Table 2. The different letter designations in the Table 2 mean that there were significant differences ($p<0.01$) for the mechanical properties among the WPC groups according to Duncan's multiple range test.

The results of Duncan's multiple range test indicated that the thermal treatment had a significant effect on the impact strength of the undecayed and decayed WPCs. There were no significant differences in the impact strength values of the undecayed WPCs between the 30 min at 180 ºC and 120 min at 150 ºC treatments. Also, there were no significant differences in the impact strength values of the decayed WPCs between the 30 min at 120 ºC, 120 min at 120 ºC, 120 min at 150 ºC, and 120 min at 180 ºC together and there is no significant difference between undecayed composites for 30 min at 180 ºC and 120 min at 150 ºC (Table 2). As shown in Table 2, the undecayed WPCs produced from the wood treated at 120 ºC for 30 min showed lower notched impact strength than the control WPC specimens but in the decayed WPCs produced from the wood treated at 180 ºC for 30 min showed lower notched impact strength than the control WPC specimens. The impact resistance of the undecayed WPCs produced from the wood treated at 180 ºC for 120 min increased by 4.5% over the control WPC specimens but the impact resistance of the decayed WPCs produced from the wood treated at 150 ºC for 30 min increased by 17.8% over the control WPC specimens. This increase was mainly attributed to the high compatibility between the wood and the polymer matrix due to the softening of lignin.

Furthermore, WPCs produced from the wood treated at 150 ºC for 30 min had slightly lower average impact resistance than the WPCs produced from the wood treated at 180 ºC for 120 min. Thus, it was expected that the treatment at 150 ºC for 30 min caused a reduction in the adhesion between the wood filler and the polymer matrix compared to the 120 min at 180 ºC specimens. The average strength loss of the samples after exposure to wood decay fungus is given in Table 3.

Table 3. Mean values of strength loss for flexural strength, flexural modulus, and impact strength measurements of the untreated and modified composites

Treatment code	Flexural strength loss (%)	Flexural modulus loss (%)	Impact strength loss (%)
A = Untreated composite	3.35	65.31	22.20
B = MC-30 min-120 ºC	3.35	64.62	-2.02
C = MC-30 min-150 ºC	2.91	63.30	-8.05
D = MC-30 min-180 ºC	6.90	65.52	18.59
E = MC-120 min-120 ºC	3.76	63.09	11.61
F = MC-120 min-150 ºC	2.27	64.14	5.07
G = MC-120 min-180 ºC	0.17	64.03	18.48

3.3 Water and thickness swelling resistance

The results of statistical analysis (Table 4) indicated that the fungal infection had direct impact on moisture absorption of the modified specimens after 6 weeks ($P<0.05$). In general, the water absorption of decayed and undecayed modified samples increases with increasing immersion time in distilled water. The absorption of water in modified samples was less compared to the control WPCs, where this case is principally due to the degradation of accessible hydroxyl groups regions on the wood surface related to the reduction of OH groups within the wood cell wall as a result of the degradation of high molecular components (Wikberg, 2004). The lower content of OH groups is responsible for less water absorption by the samples. WPCs made from thermally treated wood could decrease their equilibrium moisture content (EMC) by decreasing the accessibility of the hydroxyl groups in hemicelluloses to water; in other words, the lyses of hemicelluloses involve dehydration reactions that reduce the hydroxyl groups with a direct effect on the moisture content of thermally modified wood (Korkut et al. 2012). In addition, the formation of less hygroscopic furfural polymer from the hydrolysis of hemicelluloses under high temperature has also contributed to the reduction of EMC in wood (Tjeerdsma and Militz, 2005). Consequently, lower wood moisture content could repulse the invasion of fungus and confer better fungal resistance to the WPCs.

The water absorption of the decayed WPCs samples was higher than that of the undecayed samples for all heat-treated WPCs. It can be proposed that white-rot fungus depletes all components of the wood cell wall during decay. Therefore, the ratios of porous of the decayed WPC are increased and retain more water during soaking.

The thickness swelling of undecayed and decayed modified samples increased with increasing water soaking time. According to Table 4, higher thickness swelling was observed in the undecayed samples containing modified wood as well as control samples. The reason for the high thickness swelling of undecayed samples could be due to water absorption by available hydroxyl groups and spring back of the spongy samples exposed to fungal decomposition or the lower TS of the decayed composites could be also explained by the fact that the rot-fungi degraded the hemicelluloses in the wood cell (Hosseinihashemi et al. 2016).

Table 4. Mean value ± (standard deviation) for water absorption (WA) and thickness swelling (TS) of the untreated and modified composites

	Treatment code	WA 2 h (%)	WA 24 h (%)	TS 2 h (%)	TS 24 h (%)
Decayed	A = Untreated composite	0.62 ab (0.28)	1.63 c (0.40)	0.28 b c (0.12)	0.49 cdef (0.12)
	B = MC-30 min-120 ºC	0.95 b (0.29)	2.40 d (0.02)	0.56 def (0.13)	0.696 fg (0.11)
	C = MC-30 min-150 ºC	0.90 b (0.07)	2.31 d (0.11)	0.07 a (0.12)	0.35 bcd (0.12)
	D = MC-30 min-180 ºC	0.90 b (0.15)	2.34 d (0.34)	0.43 bcde (0.01)	0.64 efg (0.23)
	E = MC-120 min-120 ºC	0.90 b (0.14)	2.26 d (0.07)	0.21 ab (0.00)	0.49 cdef (0.11)
	F = MC-120 min-150 ºC	0.91 b (0.80)	2.01 a (0.28)	0.50 def (0.13)	0.79 g (0.14)
	G = MC-120 min-180 ºC	0.37 b (0.03)	0.99 a (0.25)	0.21 ab (0.00)	0.42 bcd (0.00)
Undecayed	A = Untreated composite	0.82 cd (0.03)	1.53 e (0.07)	2.07 ab (0.45)	2.93 b (0.72)
	B = MC-30 min-120 ºC	0.79 bcd (0.11)	1.45 e (0.20)	2.17 ab (0.38)	2.55 b (0.69)
	C = MC-30 min-150 ºC	0.81 cd (0.09)	1.41 e (0.08)	2.17 ab (0.13)	2.63 b (0.12)
	D = MC-30 min-180 ºC	0.55 abc (0.12)	0.92 d (0.19)	2.04 ab (0.52)	3.09 b (1.30)
	E = MC-120 min-120 ºC	0.77 bcd (0.05)	1.33 e (0.02)	2.74 b (0.54)	3.06 b (0.48)
	F = MC-120 min-150 ºC	0.50 ab (0.11)	1.25 e (0.48)	1.27 a (1.19)	2.60 b (0.24)
	G = MC-120 min-180 ºC	0.34 a (0.02)	0.60 abc (0.05)	2.04 ab (0.75)	2.67 b (0.29)

*Lower case letters on the numbers indicate the Duncan grouping of the averages. Values in parentheses are standard deviation (SD). Undecayed and decayed specimens were analyzed statistically and separately.

4 CONCLUSIONS

In this study, water resistance, fungal resistance, and technological properties of WPCs produced from thermally treated beech wood were investigated. Based on the authors′ study, these conclusions were obtained:

- The decay resistance of the WPCs containing thermally treated beech wood flour against the white-rot fungus (*Trametes versicolor*) improved with increasing the treatment time and temperature.
- At identical thermal treatment conditions, flexural properties and notched impact strength of undecayed WPCs were higher than those of decayed WPCs.
- As expected, the water resistance of undecayed WPCs was higher than those of the decayed WPCs.
- Based on the findings of the present study, WPCs produced using the wood treated at 180 °C for 120 minutes provide increased biological durability against wood-destroying basidiomycetes particularly possessing increased water resistance if it is exposed to ground.

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Author Contributions
Seyyed Khalil Hosseinihashemi: Creating the research idea, writing the article, performing the statistical operations, **Farhad Arwinfar**: conducting the laboratory work, taking the measurement data.

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Conflict of interest
We confirm that there is no conflict of interest.

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