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MATERIAL RESISTANCE AND MOISTURE DYNAMICS OF BEECH WOOD (*FAGUS ORIENTALIS*)

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Abstract: *In this paper, the natural durability of commercial wood (beech wood) was studied by measuring its water exclusion efficacy and durability against fungi. This information was utilized in the Meyer-Veltrup model to calculate the resistance dose. The results showed that Fagus orientalis (Lipsky) heartwood and sapwood were less durable (DC 4–5). After one hour of immersion, the water uptake in F. orientalis sapwood 19%, slightly more than that determined with F. orientalis heartwood (18.9%). Water immersion after 24 h was highest for F. orientalis sapwood (45.4%), followed by F. orientalis heartwood (40.9%). Up to 54.2% median* ML_F *on F. orientalis heartwood and up to 61.1% median* ML_F *on F. orientalis sapwood were attributed to the white fungus T. versicolor. In contrast, the lowest median* ML_F *was caused on F. orientalis heartwood and sapwood by the white fungus H. fragiforme. 35.4% median* ML_F *on F. orientalis was caused by terrestrial microcosms. Based on the resistance model, the first signs of fungal decay on F. orientalis heartwood and sapwood wood will develop after 312 and 294 days of favorable conditions, respectively.*

Key words: *beech, resistance model, water exclusion efficacy, durability.*

1. Introduction

Untreated wood used in outdoor applications is particularly vulnerable to deterioration when exposed to aboveground conditions. Despite numerous global efforts to assess wood durability, there is a lack of established methods specifically designed to classify the durability of untreated wood in aboveground settings. The existing classification system relies mainly on assessing natural resistance through field tests conducted in soil and laboratory decay tests using single-species basidiomycete cultures. The

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documentation of durability studies for wood aboveground is frequently fragmented, making it challenging to access comprehensive information. Moreover, the presentation of results often lacks clarity and conciseness. Furthermore, unlike testing in ground contact, standardized methods for assessing long-term durability in aboveground conditions are lacking. To improve the predictability of above-ground durability of wood and overcome the long exposure times needed for outdoor aboveground tests, researchers have developed performance models that include dose-response functions based on inherent durability and water performance. Meyer-Veltrup et al. [18] were the first to develop and validate a model to predict the durability of untreated wood exposed outdoors above ground. The natural durability of wood was quantitatively determined and expressed as both an absolute value and a dose with a time unit (i.e., days) in this new concept. Brischke et al. [5] applied this model to four European-grown wood species and found that *Juniperus communis* (L.) and *Taxus baccata* (L.) were classified as durable (Durability class DC 1), while *Prunus serotina* (Ehrh.) and *Sorbus aucuparia* (L.) were less durable (DC 3–5). De Angelis et al. [8] examined the resistance of *Pinus pinea* (L.) sapwood and heartwood to fungal decay using a consistent model. The results revealed that *P. pinea* (L.) sapwood falls into durability class 5, indicating its high susceptibility to fungi. On the other hand, the heartwood of *P. pinea* (L.) meets the criteria for durability class 2, signifying that it is a durable type of wood. It is important to note that durability ratings can vary depending on several factors, including wood species, location, environmental conditions, and exposure time. Therefore, it is crucial to consider all these variables when assessing the durability of wood in real-world applications. Overall, the use of performance models such as the dose-response resistance model developed by Meyer-Veltrup et al. [18] can significantly reduce the time and resources needed for aboveground durability testing of wood and optimize wood selection and treatment strategies for various applications.

Knowledge of the natural durability of wood is an essential criterion for selecting appropriate wood species for specific applications as it can help avoid various restrictions in using preservatives [24] and reduce unnecessary costs for replacing parts. Additionally, it can lead to reduced deforestation in countries like Iran, which has limited wood resources and high domestic demand for wood products. The Hyrcanian forests in Iran are the primary source of commercial timber between the northern Alborz mountain range and the southern margin of the Caspian Sea. Timber extraction for the manufacturing sector is one of the significant uses of these forests [19]. By selecting wood species based on their natural durability, the impact on residual forests can be minimized, leading to more sustainable and responsible use of forest resources. Unfortunately, some timber extracted from Iranian forests does not provide sufficient natural durability [15]. This is because when the wood remains in the forest after cutting, it becomes susceptible to various destructive factors, especially fungi, which can decrease its quality. To minimize this impact, it is recommended that wood be transported from the forest to the industry as quickly as possible. This not only helps to maintain the quality and economic value of the wood, but it also results in higher durability of the wooden products and fewer trees being cut down to supply the necessary timber. This, in turn, helps to protect forests and the environment [28]. In Iran, as in many other countries, natural durability classification has been attempted using laboratory tests and in-ground field test results, and there is a need for a method to fill the significant gaps in knowledge about Iran's natural durability, particularly in terms of natural durability used above ground in short testing periods. To address this need, the authors of this study decided to use the latest model proposed by Meyer-Veltrup et al. [1] to investigate the durability of *Fagus orientalis* (Lipsky), one of the most dominant commercial species in Iranian hardwood forests. Beech covers 17.6% of the surface area land and 23.6% of the steam number, and 30% of the standing volume of the Hyrcanian forest. Oriental beech or eastern beech is a slow-growing, shade-tolerant species reaching 30-40 m in height. Its stem diameter can reach about 1 m at breast height, and it is commonly used in plywood, veneer, furniture, benches, and construction. Different researchers have classified *Fagus orientalis* (Lipsky) as less or non-durable based on laboratory and in-ground field exposure tests [15, 17, 20]. To the authors' knowledge, there has been no documented publication on its aboveground performance. Therefore, this novel approach investigates the durability of *Fagus orientalis* (Lipsky) based on the resistance model proposed by Meyer-Veltrup et al. [18].

2. Material and Methods

2.1. Study Area

Samples of *F. orientalis* were collected from the Kheiroud district in Mazandaran province, Iran. The geographical coordinates of the collection site ranged from latitude 36° 27′ to 36° 32′ N and longitude 51° 32′ to 51° 43′ E. The samples selected for analysis were free from defects, showed no signs of decay, and were intact without any knots. The specific sections of the logs used for the analysis included the sapwood (SW) and heartwood (HW) of the *F. orientalis* samples. To conduct various durability tests, Norway spruce wood (*Picea abies*) was utilized as a reference material [18].

2.2. Durability Test against Wood-Destroying Basidiomycetes

The durability of beech wood was tested following the guidelines of EN/TS 15083-1 [6]. To prepare the specimens for wood decay fungi exposure, they were first steam-sterilized in an autoclave at 120°C for 30 minutes. The beech wood specimens were then inoculated with one of the respective fungal species, namely: the white- fungi *Trametes versicolor* (L.) Lloyd (ZIM L057) and *Hypoxhylon fragiforme*, as well as the brown rot fungus mycelium *Gloeophyllum trabeum* (Pers.) Murrill (ZIM L018).The inoculation was done in screw cap vessels measuring Ø = 105 mm and h = 80 mm, containing 100 ml of potato dextrose agar (*Difco*). The fungal isolates used in the experiment were obtained from the fungal collection of the Biotechnical Faculty, University of Ljubljana, and are available to research institutions upon request [22]. All the specimens were then incubated for 16 weeks at a temperature of 22 ± 2°C and a relative humidity of 70 ± 5%. After the incubation period, the specimens were carefully cleaned to remove any adhering fungal mycelium and weighted to calculate moisture content. The mass loss caused by the wood-destroying basidiomycete was determined gravimetrically by drying the specimens at 103 ± 2°C for 24 hours. This measurement was performed using Equation (1) as specified in the study.

$$ML_F\left[\%\right] = \frac{m_0 - m_{0,\,inc}}{m_0} \cdot 100 \qquad (1)$$

where:

ML_F is the mass loss by fungal decay [%];

$m_{0,inc}$ – the oven-dry mass after incubation [g];

m_0 – the oven-dry mass before incubation [g].

2.3. Durability Tests against Soft-Rotting

The resistance of the specimens to the soft rotting fungi was assessed using the CEN/TS 15083-2 [7] method. To simulate real-world conditions, the specimens were placed in containers filled with non-sterile compost soil and buried at a depth of 4/5 of their length. These containers were stored at a temperature of 25°C and a relative humidity of 65%. The soil moisture level was maintained at 95% of its water-holding capacity. After 16 weeks of exposure, the specimens were cleaned to remove any soil particles and mycelia attached to them. The extent of mass loss caused by fungal decay was determined by weighing the specimens before and after drying them at 103 ± 2°C for 24 hours, following Equation (1).

2.4. Durability Assessment

The durability of Iranian beech wood was calculated as the quotient (x-value, [6]) of the median ML_F of the tested timber and the median ML_F of the Norway spruce references according to Equation (2).

$$x = \frac{ML_{F,\,tested}}{ML_{F,\,reference}} \qquad (2)$$

where:

$ML_{F,tested}$ timber is the median mass loss of the tested timber [%];

$ML_{F,reference}$ – the median mass loss of the reference timber [%].

Durability classes (DC) were derived from median mass loss (ML_F) or from the different x-values according to the scheme shown in Table 1. We used two different approaches to classify the wood into durability classes. The Meyer-Veltrup model is a novel approach that is being developed [18]. Standards propose the other method which serves as a comparison.

2.5. Capillary Water Uptake Tests (CWU)

Short water absorption of material was evaluated under specific conditions: room temperature of 20°C and relative humidity of 65%. The measurement was conducted using the modified EN 1609 [9] procedure, utilizing the Krüss Processor Tensiometer K100MK2.

Table 1

Durability classes (DC) based on median mass loss ML_F, as defined by CEN/TS 15083-1 [6], based on relative $_{mean}ML_{F,\ mean}$ (x-values) according to CEN/TS 15083-1 [6] and EN 350 [11], based on relative median $ML_{F,\ mean}$ (x-values) according to CEN/TS 15083-2 [7]

Durability classes (DC)	Description	$ML_{F,\ med\ [\%]}$	x-value based on $ML_{F,\ mean}$	x-value based on $ML_{F,\ mean}$	x-value based on $ML_{F,\ med}$	x-value based on $ML_{F,\ mean}$
1	very durable	< 5	x< 0.15	x< 0.15	x< 0.1	x< 0.15
2	durable	5 < ML_F≤10	0.15 <x≤0.3	0.15 <x≤0.3	0.1 <x≤0.2	0.15 <x≤0.3
3	moderately durable	10 < ML_F≤15	0.3 <x≤0.6	0.3 <x≤0.6	0.2 <x≤0.45	0.3 <x≤0.6
4	less durable	15 < ML_F≤30	0.6 <x≤0.9	0.6 <x≤0.9	0.45 <x≤0.8	0.6 <x≤0.9
5	non-durable	> 30	>0.9	>0.9	>0.8	>0.9

This method brought the specimens axial surfaces into contact with the test liquid and they were secured in the tensiometer until a stable mass was achieved. The masses of the specimens were then recorded at intervals of 2 seconds for a total duration of 200 seconds. Capillary water uptake was determined by calculating the amount of water absorbed per unit area of the specimen over time, expressed in grams per square centimetre, using Equation (3).

$$CWU = \frac{m_{200s} - m_{65\%RH}}{A} \tag{3}$$

where:

CWU is the capillary water uptake during 200 s [g/cm^2];

m_{200s} – the mass after 200 s in contact with water [g];

$m_{65\%\ RH}$ – the mass at 20°C/65% RH [g];

A – the cross-section of specimens [cm^2].

2.6. Long-Term Water Absorption with Drying Process above Freshly Activated Silica Gel

The specimens' long-term water absorption was assessed using the leaching procedure outlined in ENV 1250-2 [12]. To begin the test, the specimens were dried in an oven at 60 ± 2°C until a constant mass was achieved, and the mass of the dry wood blocks was measured. Subsequently, the dry blocks were placed in a glass jar with weights to prevent them from floating, and 100 g of distilled water was added to each sample. The mass of the specimens was measured after 1 hour and 24 hours, allowing for the calculation of their moisture content (MC). After immersing the specimens for 24 hours, they were placed above freshly activated silica gel in a closed container for another 24 hours. The MC was then determined gravimetrically using Equations (4) and (5).

$$MC_{after\,1h}[\%] = \frac{m_0 - m_{1h}}{m_0} \cdot 100 \quad (5)$$

$$MC_{after\,24h}[\%] = \frac{m_0 - m_{24h}}{m_0} \cdot 100 \quad (6)$$

where:

$MC_{after1h}$ is the moisture content after 1h immersion [%];

$MC_{after24h}$ – the moisture content after 24h immersion [%];

m_o – the oven-dry mass before immersion [g];

m_{1h} – the mass after 1h immersion [g];

m_{24h} – the mass after 24h immersion [g].

2.7. Factor Approach to Quantify the Resistance Dose

The research employed a modeling technique inspired by the findings of Meyer-Veltrup et al. [18] and Issaksson et al. [14] to forecast how the wood species being studied would perform in real-world conditions. The model considers both the environmental exposure and the material's durability. The appropriateness of the selected design and material is evaluated using predefined acceptance criteria (Equation (6)).

$$\text{Exposure} \leq \text{Resistance} \quad (6)$$

The level of exposure can be quantified as an exposure dose (D_{Ed}), which is calculated based on daily average temperature and moisture content (MC). The material's susceptibility to decay is represented by a resistance dose (D_{Rd}). Both D_{Ed} and D_{Rd} are measured in days [d] – Equation (7), considering the ideal moisture and temperature conditions for fungal decay [13].

$$D_{Ed} \leq D_{Rd} \quad (7)$$

The exposure dose (D_{Ed}) is influenced by various factors such as driving rain, local climate, sheltering, distance from the ground, and detailed design. The development of the exposure model that accounts for these factors is described in detail in Issaksson et al. [14]. In this study, the focus was on the resistance dose (D_{Rd}), which is the counterpart of the exposure dose. The resistance dose is expressed as the product of the critical dose (D_{crit}), and two factors consider the wetting ability of wood (K_{wa}) and its inherent durability (K_{inh}). Equation (8) represents this relationship as stated in Issaksson et al. [14].

$$D_{Rd} = D_{crit} \cdot K_{wa} \cdot K_{inh} \quad (8)$$

Where **the** critical dose, known as D_{crit}, is the dose at which decay rating 1 (slight decay) occurs, as defined by EN 252 [10] (d). The wetting ability factor, denoted as K_{wa}, compares the wetting ability of the tested materials to that of the reference Norway spruce. Similarly, the inherent protective properties of the tested materials against decay, relative to the reference Norway spruce, are accounted for by the Kinh factor [4]. In this study, the moisture tests provided data to evaluate the wetting ability factor K_{wa}. The durability tests yielded results to assess the inherent resistance factor K_{inh}. Both factors were then utilized to determine the resistance dose, D_{Rd}, using Equation (8), specific to the beech wood analyzed in this research.

3. Results and Discussion

3.1. Moisture Dynamic

The water exclusion efficacy (WEE) is a crucial factor in evaluating the performance of wood species such as *Fagus orientalis*, which have lower extractive content when used above ground. Only the axial surfaces were examined to measure short-term capillary water uptake since these surfaces are typically the main pathways for water penetration and fungal infestation. Among the samples tested, *F. orientalis* SW exhibited the highest capillary water uptake at 0.611 g/cm^2, followed by *F. orientalis* HW at 0.504 g/cm^2. In long-term tests, all sample surfaces were exposed to water, and various sorption (adsorption and desorption) and capillary water uptake tests were conducted, as indicated in Table 2 and Figure 1.

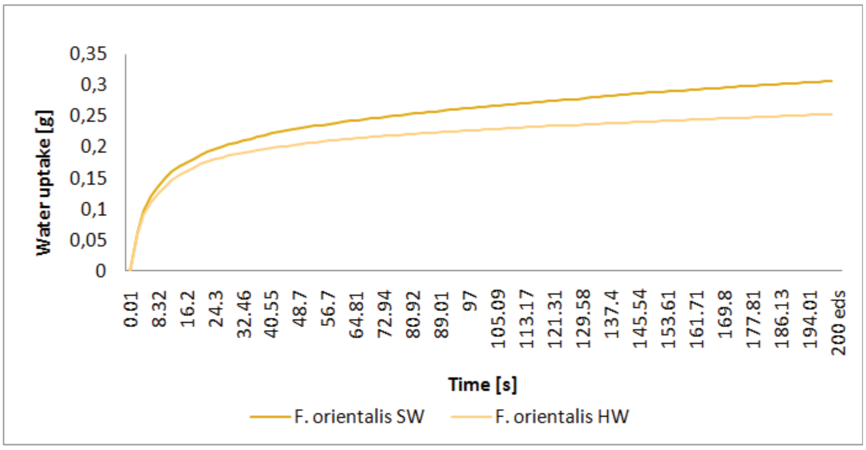

Fig. 1. *Water uptake of F. orientalis in an axial direction determined with a force tensiometer*

Short-term and long-term water uptake of *F. orientalis* Table 2

Wood species	CWU [g/cm^2]		C after 1h [%]		MC after 24 h [%]	
	Mean	SD*	Mean	SD*	SD*	Mean
F. orientalis HW	0.504	0.045	18.9	1.6	3.6	40.9
F. orientalis SW	0.611	0.053	19	2.1	2.7	45.4
P. abies	0.547	0.041	31.9	3.2	4.1	61.6

*SD – Standard deviation

After one hour of immersion, *F. orientalis* SW exhibits slightly higher water uptake (19%) than *F. orientalis* HW (18.9%), which may be due to the fungal colonization of the wood, as reported by Kržišnik et al. [16] and shown in Table 3. Water immersion after 24 hours was also found to be highest for *F. orientalis* SW (45.4%), followed by *F. orientalis* H (40.9%). Good permeability of *F. orientalis* HW was demonstrated through long-term water uptake measurements. The process of oven-drying specimens is both time-consuming and destructive, and it can potentially impact the outcomes of durability tests due to the evaporation of volatile organic compounds from the tested material under high temperatures. However, according to De Angelis et al. [8], samples not subjected to oven-drying demonstrated even greater effectiveness in excluding water than those that underwent the drying process. Ultimately, wood that possesses superior water exclusion capabilities (considering sorption properties, and short-term and long-term water uptake) exhibits better service life compared to similar wood with lower water exclusion efficacy, irrespective of its inherent durability [16].

Durability of F. orientalis after exposure to wood-degrading fungi Table 3

Wood species	Wood decay fungi									Soft root		
	H. fragiform			*T. versicolor*			*G. trabeum*			TMC		
	MC [%]	SD	ML_F [%]	MC [%]	SD	ML_F [%]	MC [%]	SD	ML_F [%]	MC [%]	SD	ML_F [%]
F. orientalis HW	26.4	4.1	116	54.2	9.1	162	35.8	2.7	105	43.5	7.9	139
F. orientalis SW	26.9	3.2	111	61.1	7.7	208	31.2	7.6	111	43.5	7.9	139
P. abies	23.79	4.6	43	23.84	41	40	34.06	7.9	46	35.4	16.7	57.7

SD – Standard deviation

3.2. Durability against Brown and White Rot Causing Basidiomycetes

Up to 54.2% median ML_F on *F. orientalis* HW and up to 61.1% median ML_F on *F. orientalis* SW were attributed to the white fungus *T. versicolor. In contrast,* the lowest median ML_F was caused on *F. orientalis* HW and SW by the white fungus *H. fragiforme*. Then, the weight loss percentage of the lignin content in the wood specimens subjected to *H. fragiforme* was well established. The minimum median ML_F of the reference species (*P. abies*) was achieved for three test fungi. Significant differences between fungal decay were checked by fundamental statistical analysis (ANOVA, LSD test at a 95.0% confidence level). The statistical analysis shows significant differences between ML_F in *F. orientalis* SW after exposure to the fungal test. Differences between fungal decay were insignificant in the median ML_F of *F. orientalis* HW subjected to the fungal test. White-rot fungi, encompassing both parasitic and saprophytic varieties, play a significant role in the deterioration of hardwood in outdoor application [16]. Bari et al. [3] expressed that over 90 percent of massive saprophytic degradation in standing and felled trees in Iran such as Oriental beech (*Fagus orientalis*) is attributed to white-rot fungi, specifically *Trametes versicolor* [16]. The white-rot fungus *Trametes versicolor* is a unique microorganism with a widespread host [2, 16]. The white-rot fungus caused extensive damage to the parenchyma cells, cellulose, and lignin, resulting in the complete destruction of Oriental beech wood [1]. Additionally, Olfat [20] found that both the heartwood and sapwood of *F. orientalis* exhibited poor resistance to decay when exposed to this particular type of fungus. MC of *F. orientalis* HW and

SW exposed to the fungus was higher than 30% and the highest MC of the *F. orientalis* SW exposed to *T. versicolor* was 208%, as shown in Table 3. The elevated moisture content is primarily attributed to water generation resulting from the depolymerisationof cell wall components by fungi [16, 25, 27]. Additionally, the decay of pits and the creation of fresh cavities also contribute to this phenomenon [21, 26].

3.3. Durability against Soft-Rotting Micro-Fungi

43.5% median ML_F on *F. orientalis* was caused by terrestrial microcosms. This value is relatively high and indicates the low durability of the respective wood species to terrestrial microcosms. This mass loss is in line with literature data and the classification of beech wood. Beech wood does not contain copious amounts of biologically active extractives; thus, high decay rates are expectable.

3.4. Durability Classification

The durability classification of *F. orientalis* was determined based on the outcomes of resistance tests conducted against brown and white rot-inducing basidiomycetes and soft-rotting micro-fungi [11]. The results of these tests are presented in Table 4. According to ML_F, *F. orientalis* HW and SW exposed to *H. fragiforme* were classified as 'less durable' (DC 4) and when exposed to T. *versicolor, G. trabeum,* they were classified as 'non-durable' (DC 5). The use of x-values (based on mean ML_F) instead of the median ML_F classified *F. orientalis* HW and SW exposed to *H. fragiforme* and *T. versicolor* as 'non-durable' (DC 5), and exposed to G. trabeum as 'non-durable' and 'less durable' (DC 4- 5). The use of x-values (based on mean ML_F) classified *F. orientalis* SW as 'less durable' (DC 4).

Durability of F. orientalis after exposure to wood- degrading fungi Table 4

Wood species	*H. fragiform*		*T. versicolor*		*G. trabeum*		TMC
	DC			x			
F. orientalis HW	4	5	5	5	5	5	5
F. orientalis SW	4	5	5	5	5	4	5
P. abies	4	5	4	5	5	5	5

3.5. Factor Approach to Quantify the Resistance Dose

Based on the resistance model and Equation (8), two factors were calculated as described in the methods and cited literature: K_{inh} (inherent durability) and K_{wa} (water performance). These factors were calculated for *F. orientalis* HW and SW wood using Norway spruce as the reference material. The factors describing the water performance and inherent durability of *F. orientalis* HW and SW wood are similar with Norway spruce. As shown in Table 5, the first signs of fungal decay on *F. orientalis* HW and SW wood develop after 312 and 294 days of favorable conditions.

Table 5

Factors accounting for the wetting ability (K_{wa}) and for the inherent protective material properties (K_{inh}) used for calculating inherent durability (D_{Rd}) and relative inherent durability (D_{Rdrel})

Wood species	D_{Rdrel}	D_{Rd}	K_{inh}	K_{wa}
F. orientals HW	1.109	0.866	312	0.961
F. orientalis SW	1.084	0.867	294	0.903
P. abies	1	1	325	1

4. Conclusion

Based on the applied test protocol, *Fagus orientalis* was categorised into two durability classes: 'less durable' (DC 4) and 'non-durable' (DC 5), considering the combined effects of wetting ability and inherent durability. The findings revealed that the relative service life of *F. orientalis* (D_{Rdrel}= 0.903 - 0.0961) closely resembled that of the reference species Norway spruce (D_{Rdrel} = 1), indicating a need for impregnation or modification. Durability was quantitatively assessed and its value provided an estimation of the conservation timeframe for *F. orientalis* in this study, which ranges from 294 to 312 days. There are insights into the point at which the species should be removed from the forest.

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