



Examination of the fire performance of wood materials treated with different precautions

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Abstract

This paper aims to discover how organic wood preservatives containing different fungicides and insecticides used to protect wood against fungal and insect pests affect the fire performance and combustion properties of wood materials commonly used in the domestic wood and construction industry. The aim of this article was to investigate the charring depth. From the point of view of the loss of load-bearing capacity of the wood, only the charring depth matters, since the reduction of the load-bearing capacity will be determined by the reduction of the cross section of the wood. We examined the effects of wood preservatives applied to undamaged samples of Scots pine and Norway spruce conditioned under normal climate conditions. The test samples underwent a second treatment application after which we examined the effect of different preservative combinations. Seven treatment mixtures were selected from the organic solvent and water-based wood preservatives available on the domestic market. The soaking experiments demonstrated that the preservative impregnation of Norway spruce differs significantly from that of Scots pine, which affected the comparability of the test results. We have experimentally investigated the moisture content, the loss of mass and we have calculated the char depth. Adhering to the MSZ 9607–1:1983 standard, the Linder method was performed to analyze the wood and wooden-based construction products used in construction. The effect of the different treatment materials was more significantly detectable when analyzing the size of the surface burn patterns. The Scots pine specimens suffered much greater surface burn than the Norway spruce specimens did, regardless of the type of preservative used. The higher body density, resin content (1–10%) and higher initial moisture content of Scots pine caused it to bend and, therefore, to burn better.

Keywords Wood · Fire · Flame retardant materials · Char depth

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Introduction

The behavior of timber under high temperatures

When the wood is heated, changes in its structure begin, which are accelerated by the increase in temperature. The three polymer components in wood begin to break down under the influence of temperature. Pyrolysis (endothermic) is the first, approximately 1 cm-wide stage that lasts from moisture loss to the flash point. The heat transfer that ensures the occurrence of the pyrolysis process characterizes the endothermic stage, which is not burning since the burning process will not be naturally self-sustaining even if the combustible gases flare up. The second stage of burning (exothermic stage) is the process in which the developed combustible gases and wood char begin to burn. The first stage extends to the outer layer of the wood char, as depicted in Fig. 1. The self-sustaining nature of combustion,

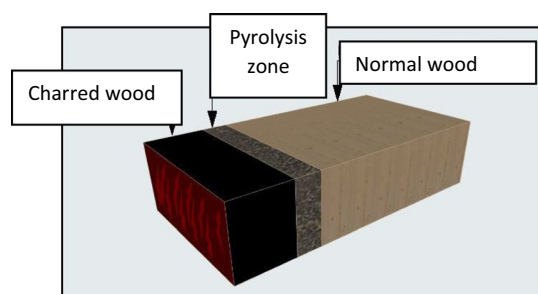


Fig. 1 Wood burning

when the generated heat promotes further pyrolysis, denotes this stage. The following process is observable when heat increases within untreated wood [1–15]:

- 100–110 °C: Drying stage: When wood temperature rises to 100 °C, it becomes chemically unbound and bound water contents begin to evaporate from the wood.
- 110–150 °C: The chemical changes begin to fasten. The wood surface changes from yellow to brown, essential oils escape, and turpentine begins to evaporate from the wood.
- 150–200 °C: After ignition, the wood begins to carbonize at a temperature of about 150–200 °C.
- 200–260 °C: The composition of the released gases changes, gas quantity increases, the combustion products released are ignited by a flame or spark. The long cellulose molecules start decomposing, which increases the amount of combustible gas that reaches the surface.
- 260–290 °C: The combustion of gaseous decomposition products is continuous; combustion becomes self-sustaining.
- 330–370 °C: Auto-flammability can occur if the environment contains enough oxygen.
- 400–500 °C: The burning of gases reaches its peak. The sharp corners, rough surfaces, flaws, and cracks in timber also increase the impact of the fire.
- Above 500 °C: The wood char burns with small flames and the heat generation process becomes intense. Temperatures may reach 1000–1200 °C.
- Afterburning: As the combustible material is consumed, the temperature drops steeply and combustion ceases following afterburning and incandescence. Between 0.2 to 1.0% of non-combustible material and ash remains.

During the pyrolysis of wood, two types of gaseous products are produced: Those that are easily released from the solid part and those that are not. Almost all of the

compounds that are broken off from cellulose and lignin in the earlier stages of pyrolysis are richer in hydrogen, oxygen, or even both than the original polymer chains. The non-volatile residue is therefore enriched in carbon. A graphitic carbon structure is formed, in which the carbon–carbon bonds are almost unbreakable. For complex gaseous products that do not readily leave the solid residue, exothermic pyrolysis still requires a higher carbon residue.

If the material is present as carbon in the solid phase, the decay of the underlying wood slows down. Although charring does not cause an increase in strength, it increases the thermal resistance between the underlying wood and the damaged wood part. This results in a decrease in the rate of heat release, thus forming a heat insulating layer.

Preventive chemical protection of timber

The preventive protection technologies for timber in the construction industry, wood, wood-based products and structures occupy two broad groups in Hungary. In particular, the so-called preventive technical wood preservation measures and the preventive preservative or chemical wood preservation technologies—which are the subject of this study—can be highlighted among the preservative-free processes [13–18]. In practice, however, a combination of technical and chemical measures is recommended for damage prevention. While the decomposing activity of wood-degrading insects and fungi is biological in origin (biotic), the burning process is abiotic. Wood protection against both biotic and abiotic effects is necessary for some installations and use conditions.

Flame retardants

Wood is a combustible material; therefore, the potential for ignition and combustion must be reduced.

Flame retardants fit into five main categories according to mechanisms of action [19].

- Mechanically acting flame retardants: These form an insulating layer on treated wood surfaces, which prevents oxygen from reaching the surface. This stops oxidation and prevents the emission of decomposed gases, all without detaching the insulation layer.
- Melt-forming retardants: When exposed to heat, these develop a melt coating on treated timber surfaces, which removes some of the heat from the environment.
- Foam-forming preservatives: These retardant forms a layer of heat-insulating foam on the surface of heat-

exposed wood. This layer prevents decomposition products from reaching the wood surface.

- Retardants that generate extinguishing gases: These retardants protect by releasing gases, such as ammonia, carbon dioxide, nitrogen monoxide, etc., when exposed to heat. They also prevent oxygen penetration into the wood.
- Carbonizing retardants: The highly concentrated inorganic acids carbonize wood surfaces under the influence of heat.

Protective substances against harmful organisms

Biocidal substances [16] are used during chemical prevention against harmful biotic organisms. Article 2(1) (a) of Directive 98/8/EC of the European Parliament defines biocidal products as active substances (containing one or more active substances) that are intended to deter, destroy, render harmless, prevent the action of, or otherwise exert a controlling effect on any harmful organism by chemical or biological means. The current study focused adequate attention on the liquid substances used in wood preservation. Many factors influence the impregnation technology of these products into the wood and its parameters. Such parameters can include wood species, moisture content, natural durability, manageability, degree of processing, anatomical direction, and species-specific biological pests. In the case of temporary protection, anti-blueing and anti-mold products can be applied

to the surface via dipping or spraying in an industrial tunnel. Saturation/impregnation may be required for some classification uses of construction timber, but this only economically viable via vacuum-pressurized live cycles rather than soaking for some timber species.

Methods for testing of wood treated with flame retardants

Table 1 shows the different test methods used to test flame retardants. Among the methods, one of the simplest and most imaginative is the Lindner method, which is why we used it for our experiments.

For our investigation, we use an easily adapted and usable method, the Lindner method, the essence of which is described in chapter 2.3.

Materials and methods

We initiated this research to investigate the impact of different flame retardants on the behavior of burning wood. Before applying the chosen substances, we determined the physical characteristics of the timber samples.

Substances used in the experiment

Timber materials used in the experiment

Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) specimens were selected for the experiments.

Table 1 Standards for test methods of wood with flame retardants

Standard	Used method	Goal of experiment
ASTM E1354 [20] ISO 5660-1 [21]	Cone calorimeter	A cone calorimeter is a device used to study the fire behavior of small samples of various materials in condensed phase
AS/NZS 3837 [22] ISO 5660-1 [21] ASTM E1354 [23] ASTM D2863 [24]	Oxygen consumption calorimeter	Oxygen consumption calorimetry (OCC) allows the measurement of the heat release rate (HRR) of a fire by the measurement of the oxygen consumed by the fire
ASTM E69 [25]	Thermo-gravimetric-differential thermal analysis	Thermo-gravimetric analysis or thermal gravimetric analysis (TGA) is a method of thermal analysis in which the mass of a sample is measured over time as the temperature changes
ASTM E6 [26]	Fire tube test	The purpose of this test method is to provide a relative measurement of the combustibility of fire-retardant-treated wood specimens based on their percentage loss in mass under controlled fire exposure conditions. In addition, other possible data include rate of weight loss, time of flaming and after glowing, increase in temperature, and maximum vertical flame progress
BS 476-Part 1 [27]	British Spread of Flame Test	The Standard dictates the appropriate fire tests for these elements of structure/materials and grades the level of fire resistance
UL 723 [28]	Surface burning	This method of test for surface burning characteristics of building materials is applicable to any type of building material that, by its own structural quality or the manner in which it is applied, is capable of supporting itself in position or being supported in the test furnace to a thickness comparable to its intended use
MSZ 9607-1:1983 [6]	Lindner method	Described in chapter 2.3

Norway spruce had a mass density of 376 kgm^{-3} and a standard deviation of 0.03, while Scots pine had a mass density of 560.43 kgm^{-3} and a standard deviation of 0.02.

Wood and wood-based products in the timber and construction industry are often made of Norway spruce or Scots pine. Both species have a significant sapwood content, which provides an ideal breeding ground for the establishment of insects and fungi. For this reason, particular emphasis should be placed on competent preventive chemical and technical protection of structural timber. According to MSZ EN 350 [29], the two species vary significantly from each other in durability and impregnability. While the mature wood of Norway spruce is classified as “less durable” (4) based on its resistance against the damage caused by basidiomycetes, the Scots pine heartwood is considered more durable (classification 3–4). The mature wood of Norway spruce is vulnerable to damage caused by house longhorn beetles (*Hylotrupes bajulus*) and common furniture beetles (*Anobium punctatum*). In terms of wood preservative treatment, the wood of both species is difficult or very difficult to impregnate (classes 3–4). However, it is noteworthy that the Scots pine sapwood is easy (class 1) to treat with wood preservatives, while that of Norway spruce is difficult (class 3) to treat. (Classification of wood impregnability: 1 easily, 2 medium, 3 difficult, 4 extremely difficult/impregnable.)

Nine $100 \times 100 \times 10 \text{ mm}$ specimens were sawn from each board. The first eight were treated with fungicide and insecticide, while the ninth specimen remained as an untreated standard. In addition, two $20 \times 20 \times 300 \text{ mm}$ specimens and three $20 \times 20 \times 30 \text{ mm}$ specimens were cut from each board to determine the strength and physical properties of the wood (Fig. 2).

Since the moisture absorption of the wood materials in the direction of the grain is very high compared to the absorption perpendicular to the grain direction, the test subjects were covered in a flexible material to prevent the applied preservatives from being absorbed into the core layer.

Once they were cut to size, the specimens were conditioned to mass stability in a climate-controlled room before the experiments. This procedure ensured the wood was

stored at a constant temperature of $20 \text{ }^\circ\text{C}$ and 65% relative humidity.

Preventive treatment agents applied

We aimed to use a variety of chemical compounds when choosing preservatives. Four protective agents were organic solvent-based, while the other three were water-based.

The preservatives selected were all approved and legally marketed products that can be used to the class 2 standard and offer chemical protection against insect and fungal pests. Wood materials are not affected by precipitation at this level of exposure, but the humidity and temperature of the surrounding ambient air vary with the time of day and season, which leads to periodic dampening of wood materials, wood, and wood-based products due to condensation [30, 31]. The active ingredients in mixtures, the effectiveness of which adheres to Reinprecht [32], are summarized below (Table 2):

1. 3-iodo-2-propynyl butyl carbamate (IPBC): This substance has been approved for use as an organic biocide for wood preservation against wood-staining fungus and molds. Fungicid Za Conazole, propiconazole, tebuconazole: 1,2,4-triazole derivates organic fungicides against basidiomycetes fungus.
2. Organic fungicides against basidiomycetes fungus (basidiomycetes + fungi).
3. Cypermethrin (CP) is a synthetic pyrethroid used as an organic insecticide.
4. Boric acid: inorganic fungicides against fungus and insects.
5. Natrium-tetraborate-decahydrate (borax): inorganic fungicides against fungus and insects used to kill parasitic fungi.
6. Alkyl dimethyl benzyl ammonium chlorides (BACs): QAC (Quaternary ammonium compounds), organic fungicide against various Ascomycota and Basidiomycota and insecticide.

Fig. 2 Method of forming the specimens

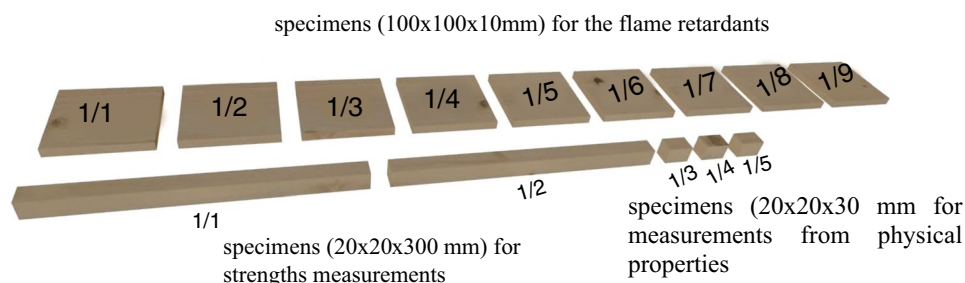


Table 2 Wood preservatives used

Type of preservative/ Name of preservative	Base	Substance/100 g retardant	Flashpoint/flammable point	Max./effective retardant penetration /Norway spruce / Scots pine [g]
Preservative 1	Organic solvent- based	1.09 g IPBC 0.35 g propi- conazole	63 °C/–	6.16/ (3.72/6.31)
Preservative 2	Organic solvent- based	1,09 g IPBC, 0.35 g propi- conazole	63 °C, > 230 °C	3.52/ (2.91/3.62)
Preservative 3	Organic solvent-based	80 g tebuconazole 0.50 g IPBC, 0.15 g cypermethrin	63 °C./–	2.71/ (2.44/2.97)
Preservative 4	Organic solvent-based	80 g tebuconazole, 0.50 g IPBC 0.15 g cyper- methrin	> 62 °C./–	2.71/ (2.74/3.09)
Preservative 5	Water-based	0.8 g IPBC, 0.8 g propicon- azole cypermethrin	> 100 °C./–	1.99/ (2.55/3.05)
Preservative 6	Water-based, salt preparation	15 g boric acid, 1.53 g borax	–/–	7.7/ (7.99/8.46)
Preservative 7	Water-soluble, heavy metal- free, liquid, concentrate	44.0 g boric acid, 0.8 g Alcyl-dimethyl, benzyl ammonium chloride	–/, 385 °C	4.4/(4.83/5.02)


Fig. 3 Treatment of specimens

When preservative amounts had to be applied in intervals, we used the higher amounts for the calculations. Preservatives 1–6 were purchased as ready-to-use products, while preservative 7 required added water to obtain a mixture

containing 5% w/v treatment agent. The preservatives seen in Fig. 1 were applied to the timber under well-controlled laboratory conditions using soaking technologies [33, 34]. The procedure was completed in hermetically sealed containers to minimize concentrate changes. Galvanized steel plates kept the specimens submerged (Fig. 3).

Periodic mass measurements monitored the preservative absorption of the prepared test specimens. Following treatment, the specimens were conditioned to mass stability under normal conditions. Flame penetration tests were conducted on the upper wooden surfaces, i.e., those that were point-fitted to the margins.

Analysis of the physical attributes of the timber materials

Table 3 gives the experimental and the number of performed experiments.

Table 3 Experimental matrix and the number of performed experiments

Type of analysis	Scots pine	Norway spruce
Moisture content	20 mm × 20 mm × 30 mm radius × chord × grain directory 27 pieces	20 mm × 20 mm × 30 mm Radius × chord × grain directory 27 pieces
Density	20 mm × 20 mm × 30 mm radius × chord × grain directory 27 pieces	20 mm × 20 mm × 30 mm radius × chord × grain directory 27 pieces

The moisture content determination (oven-drying methods for determining the moisture content of wood for physical and mechanical tests on small wood specimens)

Based on the ISO 13061 standard for determining the moisture content on small specimens during the experiment, we applied 20 mm × 20 mm × 30 mm (radial x tangential x longitudinal dimension) sized specimens (Table 3). We examined the equilibrium moisture content in the conditioned specimens at 20 °C and 65% relative humidity.

The analysis for the fire test on wood

Adhering to the MSZ 9607–1:1983 standard [6], the Linder method was performed to analyze the wood and wooden-based construction products used in construction.

Since this paper aims to answer how preventive substances affect or alter the combustion of wood treated to inhibit insects and fungi, we conducted the fire experiments in compliance with the standard mentioned above. Table 4 presents the results.

A Linder machine, depicted in Fig. 4, was used for the experiment. We placed 1 g of hexamethylenetetramine (C₆H₁₂N₄) pastille on the combustion block. We confined it with a flue when we exposed the pastille to fire. Finally, we placed the 100 × 100 × 10 mm wood specimens on a steel sheet with an 80 mm extremity.

The general principle of this examination was to assess mass loss in the specimens, which we rounded to two decimal places both before and after combustion.

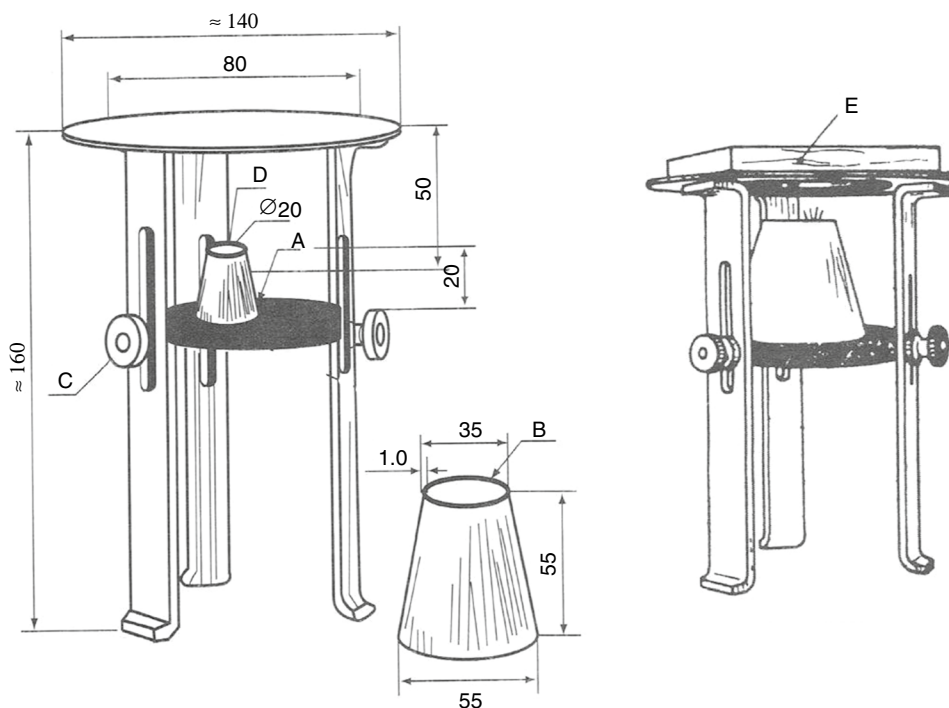
The standard defines a flame retardant as effective if mass loss does not exceed 1.5 g for surface-treated wood and 2.5 g for impregnated wood.

To investigate the effect of the different preservatives on the char depth of the specimens, we sawed the first four specimens in half along the center of each specimen. These cut specimens aided in the visual inspection of the surfaces and the examination of mass loss. Despite the inhomogeneity of the wood materials, we assumed that the maximum penetration depth could be measured in the middle section most exposed to the combustion flame. To obtain the maximum depth of penetration of each specimen as a function

Table 4 Experimental matrix of combustion of wood with preservative protection

Type of wood	The assigned number of the preservative						
	1	2	3	4	5	6	7
Norway spruce	8	8	8	8	8	8	8
Scots pine	8	8	8	8	8	8	8

Fig. 4 Linder Machine [6]



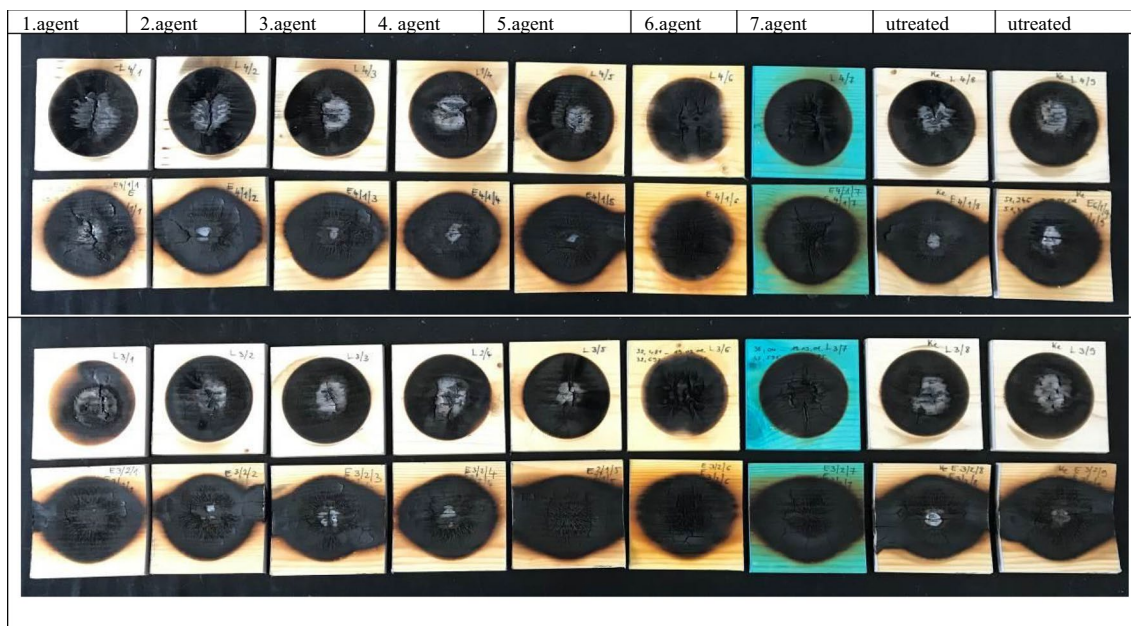


Fig. 5 Surface charring according to type of treatment agent used

of the different preservatives, we evaluated the results by subtracting the minimum thickness of the zone remaining intact in the center of the specimen from the initial cross sectional thickness of the specimen.

Results and discussion

The moisture content of the wood materials

Norway spruce had a moisture content of 9.32% and a standard deviation of 0.52, while Scots pine had a moisture content of 10.87% and a standard deviation 0.49.

Results of fire tests

Visual observation

A visual observation was completed after the Linder test (Fig. 5).

We have the following conclusions from the visual observation:

- In the case of preservative 6, as soon as the flame reached the wood, the boric acid component within the treatment caused the outer zone of the flame plume to turn a greenish hue.



Fig. 6 Visible cracking of the test samples

- Scots pine suffered much higher surface burns and burned better than Norway spruce specimens, which were bent due to the higher body density, higher resin content (1–10%) and higher initial moisture content.
- Except for preservative 6, the use of different protective agents typically did not affect the extent of surface burning. Even with the high resin content of Scots pine, preservative 6 retarded surface burning of the specimens, thus showing the most favorable surface burn size. This treatment, therefore, had a remarkably positive effect on the surface burn size of the wood.



Fig. 7 Concave deformation of Scots pine

Cracks appeared on the surface of charred specimens. Parallel with the grain direction of the samples, cracks were few and small. Conversely, cracks were larger and more abundant perpendicular to the wood grain direction. This effect occurred mainly in the Norway spruce specimens. We concluded that the previously mentioned cracks appeared on the spruce specimen surfaces where the flame contacted the wood; however, the flame created “sparkler” like patterns on the Scots pine specimens (Fig. 6). Cracks that were small in size and few in number formed in parallel with the fiber direction of the wood, while more abundant and larger cracks formed perpendicular to the fiber direction. The cracks, which were visible in larger numbers on spruce specimens, were observed because of burning. The above-mentioned cracks formed around the flame contact point on the surface of the Norway spruce

Fig. 8 Average specimen mass loss (g) (first row, Norway spruce; second row, Scots pine)

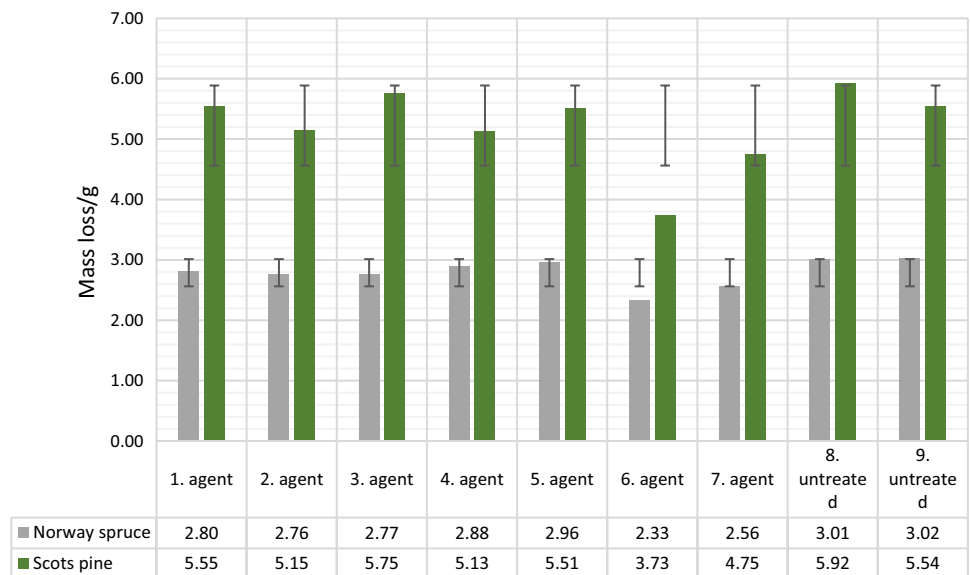


Fig. 9 Average specimen mass loss (%)

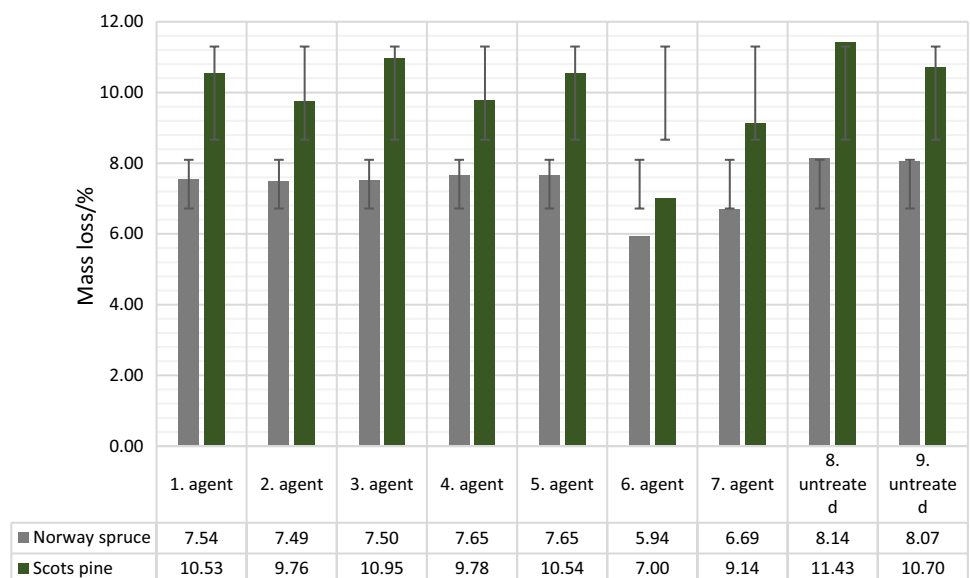
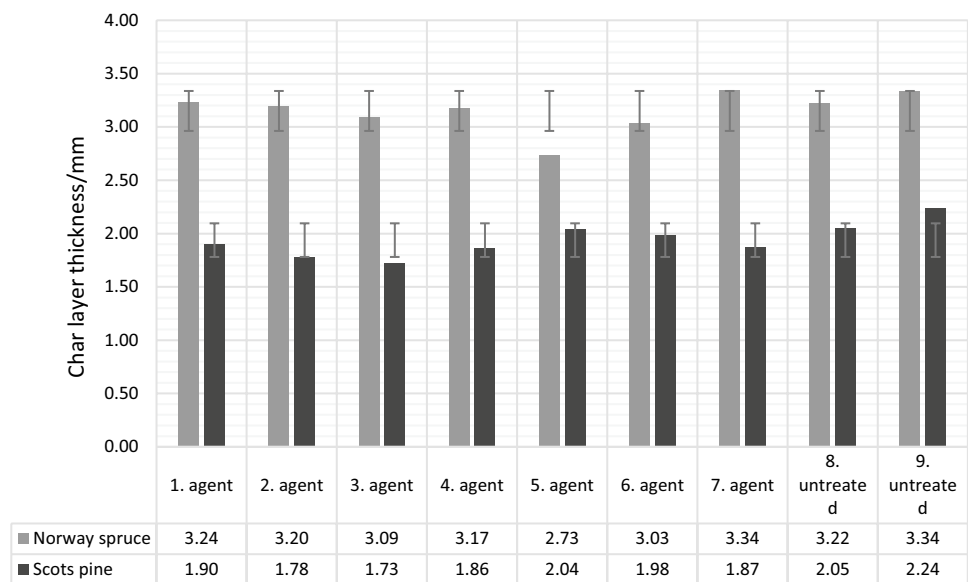


Fig. 10 Average char layer thickness on the test specimens (mm)



specimens, while a “sparkler” -like pattern emerged from the center on the charred surface of the pine (Fig. 6).

In certain cases, sample deformation became apparent following the fire test. A significant proportion of the specimens curved inward on the flame exposed side, which is noteworthy because according to the literature Scots pine is less likely than Norway spruce to deform under normal conditions without having been exposed to fire according (Fig. 7).

Mass loss

Eight tests were performed on the wooden specimens and retardants. We then calculated the average of each measurement in grams (Fig. 8) and in mass percentage. (Fig. 9.). The bar graphs below present the results.

The results clearly indicate that none of the treatments qualifies as a good flame retardant since every specimen suffered mass loss that exceeded 1.5 g. We can also conclude that the use of different preservative agents influences the mass loss that occurs during specimen burning.

The use of solvent-based treatment agents 1–4 on spruce specimens yielded nearly identical mass loss results, while water-based, treatment agent number 5 also had similar results. Treatments 6 and 7 were water-based treatment, and they yielded the lowest specimen mass loss. Specimens 8 and 9, which were untreated, experienced the greatest mass loss. We can conclude that the treated and untreated specimens had mass loss quantities despite the chemical compounds within the tested treatment agents.

The Scots pine and Norway spruce specimen data are rather similar, but due to the larger degree of surface char, the standard deviation is also higher.

Char depth

Figures 10 and 11 demonstrated the cross sectional area measurements of the first four specimens, which were sawn in half down the middle. These measurements are plotted as a function of char layer thickness and char depth for each species and treatment agent.

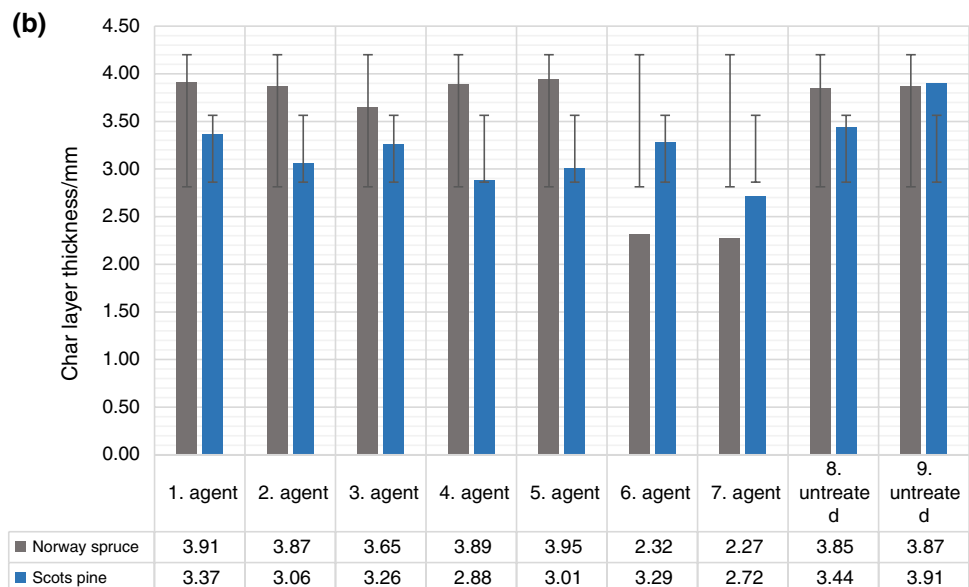
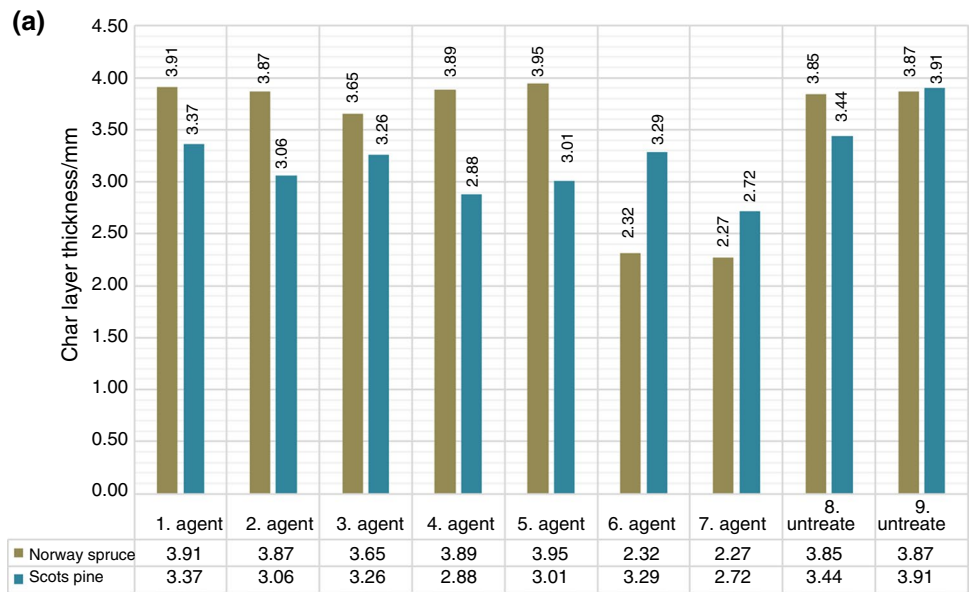
While analyzing the scale of the surface combustion images, we could see that the different treatment agents did not significantly affect charring zone thickness. Nevertheless, two water-based treatment agents in the case of Norway spruce and two solvent-based treatment agents in the case of Scots pine did reduce charring thickness slightly.

Though specimens treated with preservative 6 exhibited the best results in the previously conducted experiments, it had no remarkable effect on the charring zone thickness of the specimens.

An interesting phenomenon also became observable. Charring zone thickness was much higher in Norway spruce specimens than in Scots pine specimens. The physical and chemical composition differences between the species explain this.

Figure 11 reveals that the most favorable results, based on char depths, were from the test specimens treated with water-based treatment agents. It is interesting to note that the char depths were deeper in Norway spruce specimens than they were in Scots pine specimens with every preservative. The only exceptions were the Norway spruce samples treated with treatment agents 6 and 7, which were water-based.

In the case of Scots pine, the density of which was 560.43 kgm^{-3} , calculated with a burning time of 2.9 min, the rate of

Fig. 11 Highest average specimen char depths (mm)

charring was $0.53\text{--}0.68\text{ mmmin}^{-1}$, which is a higher value than the value specified in EN 19,951-2 [5] (0.65 mmmin^{-1}).

In the case of Norway pine, the density of which was 376.00 kgm^{-3} , calculated with a burning time of 2.9 min, the rate of charring was $0.78\text{--}1.15\text{ mmmin}^{-1}$, which is a higher value than the value specified in EN 19,951-2 [5] (0.65 mmmin^{-1}).

In the case of Scots pine, the charring speed specified in EN 1995-1-2 can be used, but in the case of Norway pine, the values given in EN 1995-1-2 significantly underestimate the real value, which can be explained by the high resin content and moisture content of the wood.

Conclusions

This paper aimed to understand how organic wood preservatives containing insect control and fungicides might affect the burning properties of wood materials used in the domestic construction and timber industry. We examined the effect of wood preservatives applied to undamaged, naturally conditioned Norway spruce and Scots pine samples. The test samples underwent two treatments, after which we examined the effect of different preservative combinations. Seven mixtures were selected from the organic solvent-based and water-based products available on the domestic market.

The effect of the different treatment materials was more significantly detectable when analyzing the size of the surface burn patterns. The Scots pine specimens suffered much greater surface burn than the Norway spruce specimens did, regardless of the type of preservative used. The higher body density, resin content (1–10%) and higher initial moisture content of Scots pine caused it to bend and, therefore, to burn better.

Except for treatment agent 6, the use of different preservatives typically did not affect the extent of surface burning. Even with the high resin content of Scots pine, treatment 6 retarded the surface burning of the specimens, thus showing the most favorable burn size. This treatment, therefore, had a remarkably positive effect on the size of surface burn on wood.

Cracks appeared on the surface of charred specimens. We observed smaller and fewer cracks parallel to the wooden samples grain direction while larger and more abundant cracks appeared perpendicular to the wood grain direction when burned. This effect occurred mainly with the spruce specimens. We concluded that the previously mentioned cracks appeared on the spruce specimen surfaces where the flame contacted the wood; however, the flame created “sparkler” like patterns on the Scots pine specimens (Fig. 6). Smaller and fewer cracks were formed in parallel with the fiber direction of the wood, while larger and more cracks formed perpendicular to the fiber direction. All these cracks occurred because of burning, and they appear in greater abundance on spruce specimens. We found that the above-mentioned cracks formed around the flame contact point on the spruce specimen surfaces, while a “sparkler” -like pattern emerged from the center on the burning surface of the pine (Fig. 6).

The use of solvent-based preservatives 1–4 on spruce specimens yielded nearly identical mass loss results, while water-based, preservative 5 also had similar results. Treatments 6 and 7, which were water-based, had the lowest specimen mass loss. Specimens 8 and 9, which were untreated, experienced the biggest mass loss. We can conclude that the treated and untreated specimens all experienced mass loss quantities despite the chemical compounds within the tested treatment agents.

The different wood preservatives did not significantly affect charring zone thickness; however, two water-based agents applied on Norway spruce and two solvent-based agents applied on Scots pine did slightly reduce charring thickness.

Specimens treated with preservative 6 had shown the best results in the previously completed experiments. However, it is intriguing that not even preservative 6 exhibited any noteworthy effect on the charring zone thickness of the specimens. Charring zone thickness was higher in Norway spruce specimens than in Scots pine specimens. The physical

and chemical compositions of the two species explain this difference.

Irrespective of the fact that none of the tested preservatives met the standard for flame retardancy, the present study was also confirmed that, depending on the different active ingredient compositions, the preservatives had a positive effect on the flame retardancy of wood materials in several cases.

In the case of Scots pine, the charring speed specified in EN 1995-1-2 can be used, but in the case of Norway pine, the values given in EN 1995-1-2 significantly underestimate the real value, which can be explained by the high resin content and moisture content of the wood.

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Declarations

Conflict of interest We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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References

1. Walker A (2006) The anatomy of wood. In: The Encyclopedia of wood, Cser Press, Budapest. p. 8.
2. MSZ EN 335-2: 2007 (2007) Durability of wood and wood-based products. Definition of use classes. Part 2: Application to solid wood.
3. MSZ EN 460:1997 (1997) Durability of wood and wood-based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes.
4. MSZ EN 1995-1 (1995) Eurocode 5 Design of timber structures.
5. MSZ EN 1995-1-2:2013 (2013) Eurocode 5 Design of timber structures. Chapter 1-2 Part 1-1: General - General - Structural fire design.

6. MSZ 9607–1:1983 (1983) Fire protection. Testing of wood and wood substituting materials treated with flame retardant substances. Method of Lindner.
7. Government Decree 253/1997. (XII. 20.) (1997) on the national requirements regarding town planning and construction.
8. MSZ EN 13501–1:2019 (2019) Fire classification of construction products and building elements. Part 1, Classification using data from reaction to fire tests.
9. Decree 54/2014 (XII.05) (2014) of the Ministry of Interior on the National Fire Protection Regulations.
10. Official Journal of the European Union EC Decision 2003/593/EC (07.08.2003), amending Decision 2003/43/EC establishing classes of reaction-to-fire performance for certain construction products.
11. Molnár S, Farkas P, B6rcs6k Z, Zoltán Gy. (2016) Physical and Mechanical characteristics of wood In: Industrial timbers of Earth, Sopron: ERFARET Ltd., (in Hungarian).
12. Király B, Csupor B. The stages of the burning of wood in Materials and mixtures of the chemical wood and fire protection. Gy6r: Platina Press and Press Ltd.; 2013. (in Hungarian).
13. Igmány Z. Wood protection. In: Lugosi A, editor. Wood construction handbook Budapest. Technical Press; 1976. p. 260–78 (in Hungarian).
14. Horvath N (2008) Applied wood protection in the effect of thermal treatment on the properties of wood, with special regard to fungal resistance. Doctoral dissertation, University of West Hungary, (in Hungarian).
15. Qu H, Wu W, Jiao Y, Xie J, Xu J. Investigation on the thermal decomposition and flame retardancy of wood treated with a series of molybdates by TG–MS. *J Therm Anal Calorim.* 2011;105(1):269–77.
16. Budrugaec P, Emandi A. The use of thermal analysis methods for conservation state determination of historical and/or cultural objects manufactured from lime tree wood. *J Thermal Anal Calorim.* 2010;101(3):881–6.
17. Gao M, Sun C, Wang C. Thermal degradation of wood treated with flame retardants. *J Thermal Anal Calorim.* 2006;85(3):765–9.
18. Sebo-Punal T, Naya S, L6pez-Beceiro J, Tarro-Saavedra J, Artiaga R. Thermogravimetric analysis of wood, holocellulose, and lignin from five wood species. *J Therm Anal Calorim.* 2012;109(3):1163–7.
19. Nemeth L. The design for fire resistance of wood structures 9.3. The mechanism of fire retardants' in Wood materials and wood protection in the construction industry. Budapest: Agroinform Press; 2003. (in Hungarian).
20. ASTM D1413, Standard Test Method for Wood Preservatives by Laboratory Soil-Block Cultures. ASTM International
21. AS/NZS 3837, Method of Test for Heat and Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter. Standards Australia/Standards New Zealand, 1998.
22. ISO 5660–1, Reaction-to-fire Tests–Heat Release, Smoke Production and Mass Loss Rate–Part 1: Heat Release Rate (Cone Calorimeter Method). The International Organization for Standardization.
23. ASTM E1354, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter. ASTM International.
24. ASTM D2863, Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index). ASTM International.
25. ASTM E69, Standard Test Method for Combustible Properties of Treated Wood by the Fire-tube Apparatus. ASTM International-Return to ref 20 in article.
26. ASTM E108, Standard Test Methods for Fire Tests of Roof Coverings. ASTM International.
27. ASTM E906, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products. ASTM International.
28. UL 723, Test for Surface Burning Characteristics of Building Materials. Underwriters Laboratories.
29. MSZ EN 350 MSZ EN 350:2016 (2016) Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials.
30. MSZ EN 15228:2009 (2009) Structural timber. Structural timber preservative treatments against biological attack.
31. MSZ EN 351–1:2008 (2008) Durability of wood and wood-based products. Preserved solid wood. Part 1: Classification of Pesticide Penetration and Pesticide Uptake.
32. Reinprecht L. Ochrana dreva in Wood protection Handbook. Zvolen-Slovakia: Technical University in; 2008. (978-80-228-1863-6).
33. Official Journal of the European Union (1998), Directive 98/8 / EC currently governs the European authorization of biocides. Regulation (EU) No 528/2012 concerning the marketing and use of biocidal products.
34. Official Journal of the European Union (2012), Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the placing on the market and use of biocidal products Text with EEA relevance.

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