FIRE PROTECTION & SAFETY Scientific Journal
16(2): 15–23, 2022
DOI: 10.17423/delta.2022.16.2.111

Wood in Building Structures and its Fire Protection

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Original scientific paper

Received: October 17, 2022; Accepted: October 31, 2022; Published: December 31, 2022

Abstract

The research is oriented towards the fire protection of wood, mainly with chemical protective agents, which aim at suppressing the various reaction processes in the material that are induced by the thermal loading. One of these substances is HR-Prof, a fire protection agent designed to protect wood, wood products and cellulose. Once applied (by painting, spraying, immersion or vacuum method), this substance allows the natural appearance of wood to be preserved and is suitable to be used both indoors and outdoors. The aim of the experiments carried out was to compare the behaviour of thermally loaded spruce wood after treatment with HR-Prof (2x coating; in the quantity specified by the manufacturer) and untreated. The variables compared were the mass loss of the test samples, the time to ignition, the relative rate of burning and, above all, the effect of the environment (interior, protected exterior and exterior), to which the wood samples were exposed for one month, on the effectiveness of the retardant and the variables evaluated. Summarising the results, it was confirmed that the application of the fire-retardant coating to spruce wood contributed to an increase in its thermal stability (lower mass loss, increase in time to ignition), although with the observation that the final results of the above evaluation criteria were significantly affected by the environment to which the samples were exposed. The samples stored outdoors, where they were directly exposed to the weather, clearly showed the worst results, the samples stored in a sheltered outdoor environment showed a more favourable result and the samples stored indoors were the best in the evaluation. The final conclusion for the practitioner and user is therefore that HR-Prof is clearly preferable for the protection of wood placed in an interior environment, alternatively a systemic protection solution should be chosen, i.e., a combination of this protective agent with a suitable top (anchoring) coating.

Keywords: spruce wood; fire retardant; mass loss; ignition time; relative rate of burning

1 Introduction

Wood is an organic material, classified as a natural lignocellulosic polymer. Due to its good technical, aesthetic, and other advantageous properties, it has been known and used as a building material by human ancestors for centuries. However, its main disadvantage is that it requires constant maintenance - it is susceptible to damage by abiotic and biological agents and is flammable. The resistance of different types of wood to deterioration by abiotic agents (water, sun, oxygen, etc.) and biological agents (fungi, bacteria, insects) is referred to as the natural durability of wood. It depends on the species of wood, its structure and the susceptibility of the basic components - organic polymers (cellulose, hemicelluloses and lignin) - to these agents. Damage to the organic polymers of wood also plays an important role in the degradation processes to which wood is subjected at higher temperatures, either by direct exposure to flame or by other high-temperature activation sources. Polymers are split and flammable gases are formed. These react with oxygen at a sufficiently high temperature in various thermo-oxidation reactions of an exothermic nature, carbon oxides and water are formed, and a considerable amount of energy is released [1]. In terms of reaction to fire, according to EN 13501-1 (2019) [2], wood is usually classified as Class D, which means that it can contribute significantly to the development of a fire in a building.

Therefore, the care of this material is an essential requirement for the unlimited use of wood in building structures.

The continuous improvement of methods and tools for acquiring knowledge of the structure and properties of wood has gradually expanded, and is still expanding, the knowledge of ways of increasing its resistance to the above-mentioned damages. For construction timber, various methods of protection are being implemented in practice, which can be suitably combined. According to Reinprecht and Štefko et al. [1, 3], this is mainly a combination of structural, chemical, physical and fire protection measures, depending on the anticipated threat. Structural protection is based on the optimization of the exposure conditions of the wood and the use of more durable species. Physical protection consists, for example, in sterilising the wood with heat or UV radiation, while chemical protection uses substances with different directional effects (biocidal, UV-sorbing, fire-resistant, etc.). Intensive research to increase the resistance and durability of wood is also currently being carried out in the application of nanoparticles. According to Kubovsky et al. [4] allow to increase its photostability, resistance to wood-destroying fungi, insects, but also to fire. Also, the results of Reinprecht and Vidholdova [5] as well as Boonstra and Tjeerdsma [6] confirmed that the biological resistance of wood is significantly increased by its thermal modification.

Although there are currently various ways of increasing the fire safety of wood (dry and wet technologies), one of the most widely used is the treatment with coatings (fire retardants). These are substances suppressing various reaction processes in the material induced by the thermal loading [7]. Using them, it is possible to implement high-quality and cost-optimized solutions depending on the required fire resistance of the structural element. Many of them allow to preserve the original appearance of the wood and can be applied directly in production or at the place of use.

The mechanism of action of these substances varies. They reduce the flammability of materials by physical or chemical means, but most often the synergistic effect of both is used. They either prevent oxygen from reaching the surface of the wood, or thermally insulate the wood substance from the heat source, or dilute the flammable gases produced during the thermal decomposition of the wood or prevent the oxidation of the carbon in the charcoal layer to carbon dioxide.

In practice, mainly water-based systems are used, either as concentrated solutions of suitable inorganic salts (ammonium phosphates, ammonium sulphates, ammonium chlorides, etc.) or as water-based dispersions of suitable polymers with the addition of retarding and foam-forming components ('intumescent coatings'). Combinations of nitrogenous substances with phosphorus compounds are particularly preferred. The phosphorus-containing compounds undergo dehydration and carbonisation to form protective carbon layers, the presence of nitrogen helps to absorb heat and produce non-decomposition of the polymers. The synergistic effect of nitrogen and phosphorus on the suppression of the combustion process has been confirmed also by Bogdanova et al. [8]. Similarly, Grzeskowiak [9] states that an increase in the number of nitrogen atoms in the formulation provides a higher efficiency of the flame retardant. The nanomaterials are nowadays perspective in the field of flame retardant protection. For example, the retardant effects of phosphorus in various combinations are being investigated, e.g., phosphorus-modified wheat starch [10], phosphorylated cellulose nanofibers [11], phosphorus-modified lignin nanoparticles [12]. Research is also focusing on the use of titanium dioxide and zinc oxide [13], also silica [14,15], or a combination of the two has been applied. In their work, the authors [16] highlight the retarding effect of sodium silicate in combination with expandable graphite particles.

2 Material and Methods

The research is focused on wood fire protection. It focuses primarily on the protection by chemical coatings, as documented by the experimental results presented in the following sections of this paper. In particular, the evaluation of the thermal resistance of retardant-treated spruce wood with HR-Prof, under the thermal loading by radiant heat source.

The HR-Prof retardant is a manufacturer's product for both interior and exterior use. This was the reason for its selection for the treatment of the test wood samples.

The aim of the experiments carried out was to evaluate whether the environment (interior, protected exterior and exterior) to which the treated spruce timber was exposed would affect the effectiveness of the retardant used and thus the resistance of the spruce timber under fire conditions.

The results of the evaluated groups of treated samples were compared with the results of the evaluated groups of chemically untreated samples.

2.1 Preparation of samples

Wood samples of Norway spruce (*Picea abies L.*) with dimensions of 50 x 40 x 10 mm were used for the experiments. The samples were divided into three groups consisting of 10 pieces each, cleaned and stripped of sharp edges. For each group evaluated, half of the samples were surface treated with the retardant HR-Prof, the other half remained untreated (control samples). The coating was carried out using a brush in two layers (24 h apart), using the following application rate: 0.6 g/1 sample/1 layer (this is the calculated amount according to the manufacturer's recommendations). The samples thus prepared were placed in a metal frame fitted with a grid (Fig. 1).

Fig 1. Storage of test samples: (1) adjustable metal stand; (2) metal frame with mesh for placing test samples; (3) test samples (untreated and treated with HR-Prof).

The first group of test samples prepared this way was stored in an outdoor unprotected environment (outdoors), the second group in an outdoor protected environment (under shelter) and the third group in an indoor (laboratory) environment. After one month, samples from each environment were collected and stored in a desiccator for acclimatization and comparability of results. The moisture content of all samples after removal from the desiccator was 6%. Subsequently, the samples were tested.

HR-Prof [17] - is the trade name of a substance intended for fire protection of wood and cellulose products (e.g., wooden trusses, coffered ceilings, wooden floors, tiles, etc.). It is a water-based solution of ferric phosphate, citric acid, and special additives. The preparation has a high ability to diffuse into the structure of the material, the treated material has a self-extinguishing character. It provides an increase in fire resistance of the protected structure by 10 min.

2.2 Method of testing

The wood samples were loaded with a radiant heat source. This is a non-standard test method (Fig. 2) which allows continuous recording of the change in mass of the test material, time to ignition and evaluation of the measured results by means of a computer program during the thermal loading with the radiant heat source.

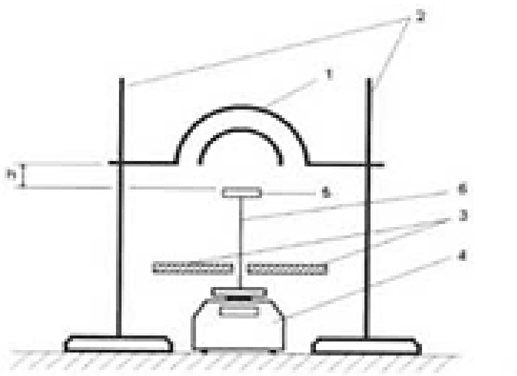

Fig 2. Scheme of the test equipment: (1) infrared radiation source with a power of 1 kW; (2) metal supporting frame; (3) scales protection plates; (4) electronic scales; (5) test sample; (6) stand for placing the test sample.

The total duration of the test is 10 min (time representing approximately the first phase of the development of a standard structural fire). From the measured values, the relative mass loss and the relative rate of burning are calculated according to the following equations:

$$\delta_m(\tau) = \frac{m(\tau_0) - m(\tau)}{m(\tau_0)} * 100 \qquad (\%) \qquad (1)$$

$$v_r = \frac{[\delta_m(\tau) - \delta_m(\tau + \Delta\tau)]}{\Delta\tau} \qquad (\%/s) \qquad (2)$$

Where:

$\delta_m(\tau)$ - relative mass loss over time (τ) (%);
v_r - the relative rate of burning(%/s);
$m(\tau_0)$ - original mass of the sample (g);
m(τ) - mass of the sample at time (τ) (g);
δ_m $(\tau + \tau\,\Delta)$ - relative mass loss over time (τ + Δτ) (%);
$\Delta\tau$ - time interval at which the masses are recorded (s).

3 Results and Discussion

The results of the completed experiments are presented in tables (Tab.1-2) and graphs (Fig. 3-9). In summary, it is an evaluation of the effect of fire-retardant treatment on the thermal resistance of spruce wood and an evaluation of the effect of the environment to which this material was exposed (interior, protected exterior and exterior) on the effectiveness of the applied protective substance HR-Prof. The evaluation criteria were the mass loss, the ignition time and the relative rate of the material burning for the specified test time of 600 s, under the action of radiant heat. These evaluation criteria were used for all evaluated groups, i.e., for both retardant-treated and untreated ("control") spruce wood samples. The results are presented as average values of five measurements.

Tab. 1 Final values of mass loss and time to ignition of untreated and retardant-treated spruce wood samples.

Environment	**Untreated samples**		**Treated samples**	
	Mass loss (%)	Ignition time (s)	Mass loss (%)	Ignition time (s)
Interior	68	95	48	155
Protected exterior	85	61	71	92
Exterior	90	37	89	37

Tab. 2 Values characterizing the burning rate and time of maximum burning rate of untreated and retardant-treated spruce wood samples.

Environment	Untreated samples		Treated samples	
	Maximum rate of burning (%/s)	Time of achieving the maximum rate of burning (s)	Maximum rate of burning (%/s)	Time of achieving the maximum rate of burning (s)
Interior	0.23	150	0.10	150
Protected exterior	0.28	70	0.20	110
Exterior	0.39	70	0.41	60

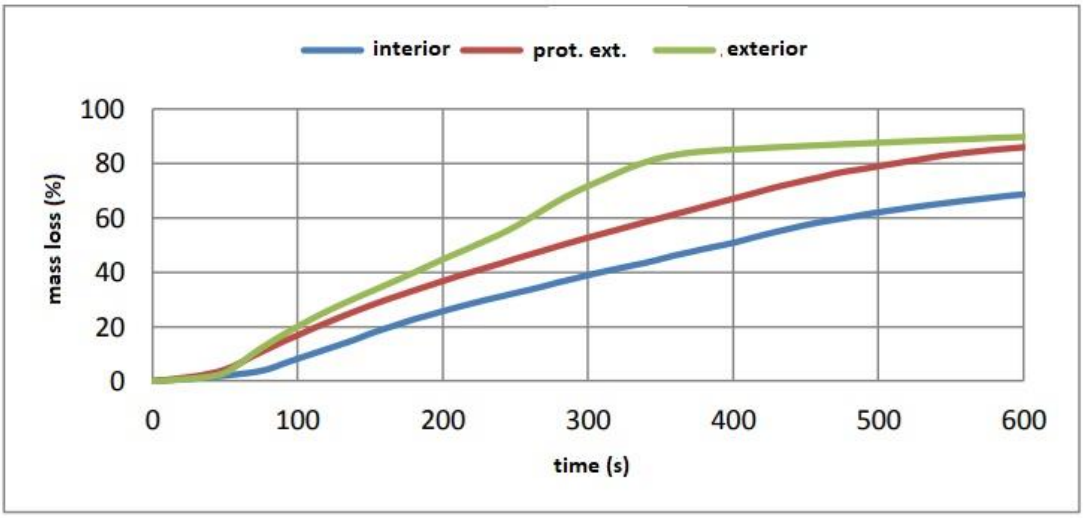

Fig 3. Effect of environment on mass loss of untreated spruce samples.

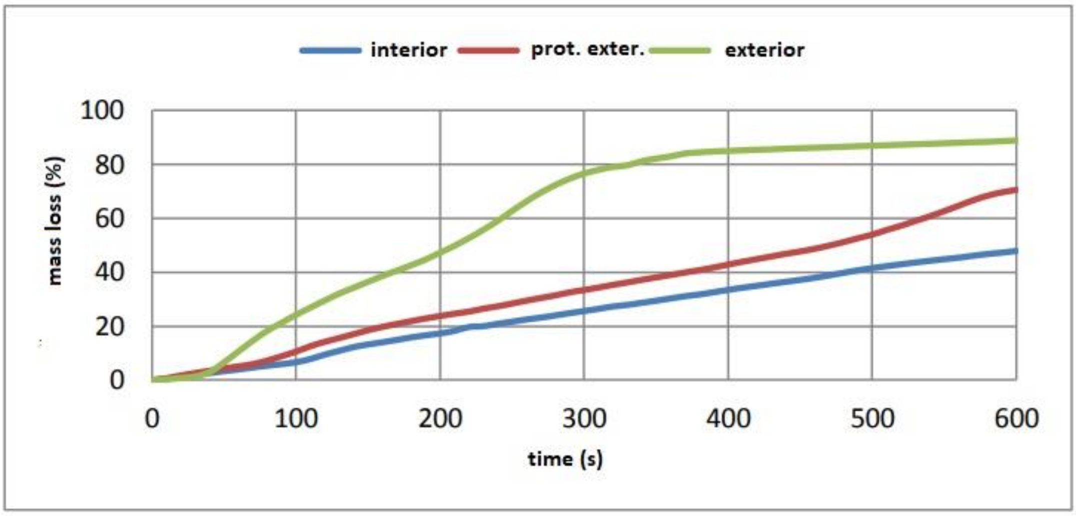

Fig 4. Effect of the environment on the mass loss of spruce samples with application of the retardant HR-Prof.

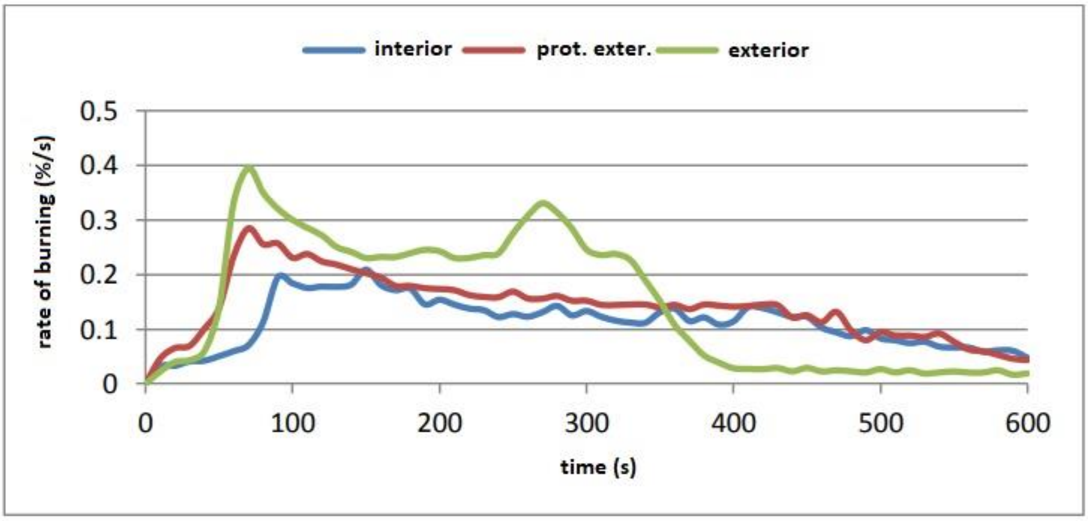

Fig 5. Effect of the environment on the rate of burning of untreated spruce samples.

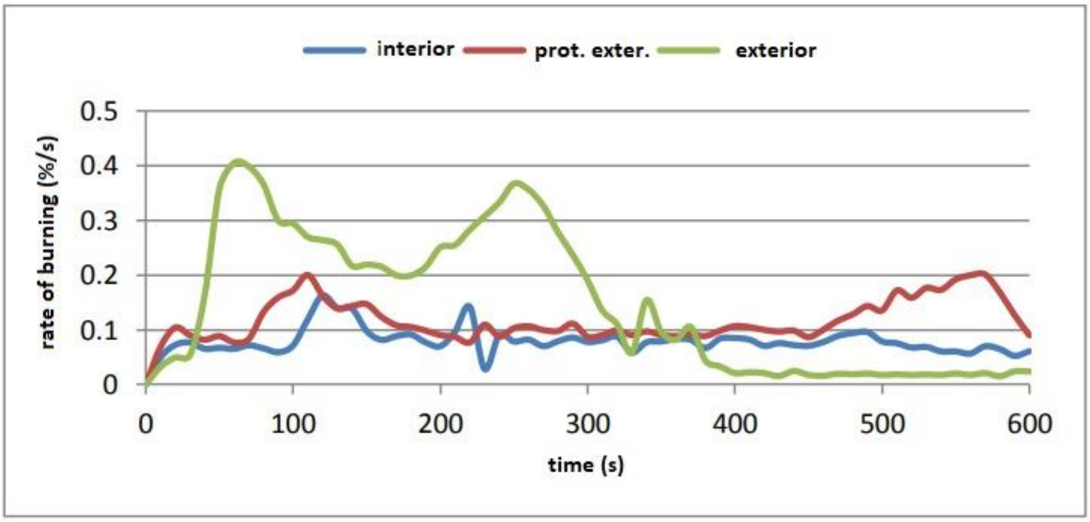

Fig 6. Effect of the environment on the rate of burning of spruce samples with application of the retardant HR-Prof.

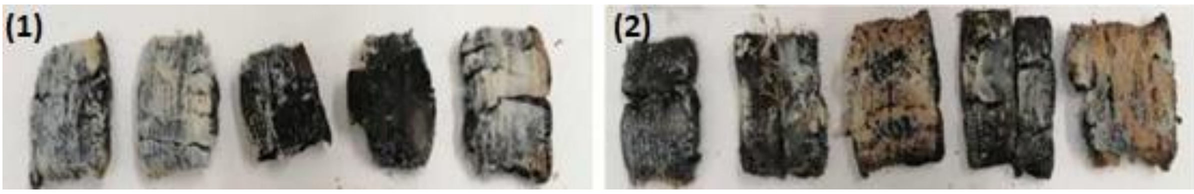

Fig 7. Spruce wood samples after the test (stored in an unprotected exterior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

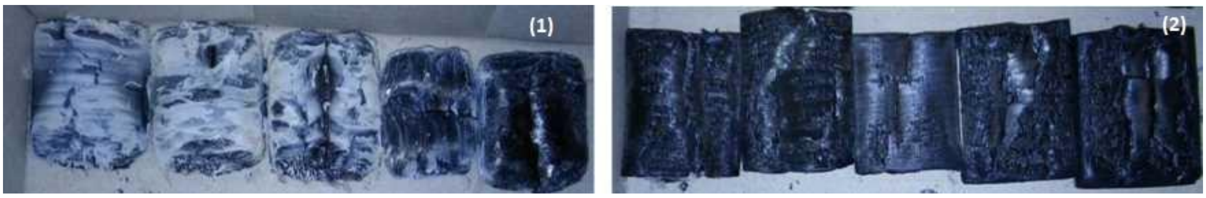

Fig 8. Spruce wood samples after the test (stored in a protected exterior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

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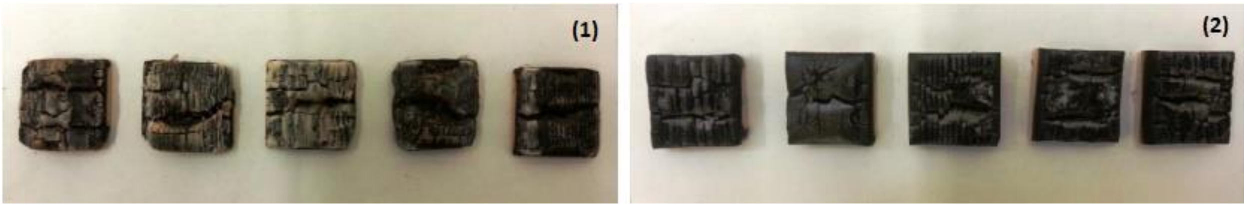

Fig 9. Spruce wood samples after the test (stored in an interior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

The evaluation documented in Tab. 1 and 2 and Figs. 3 to 9 showed that the environment to which the spruce wood was exposed, both untreated and retardant treated, had a significant influence on the change in its properties. The external environment (exterior) and the change in weathering have been shown to contribute to a more significant deterioration in its fire properties. Samples taken from this environment (although they were then conditioned to exclude the influence of humidity) degraded after subsequent thermal loading in the presence of flame. Their surface ignition occurred shortly after being placed in the thermal loading environment (on average at 37 s) and they lost on average 90 % of their original mass during the time of testing. An interesting finding of this first group evaluated is that even retardation treatment of the samples did not ensure an improvement in their properties. Comparing the curves in Figs. 3 and 4 and from Tab. 1, the mass loss of the treated samples is only 1 % lower compared to the untreated samples, and that they started to burn at the same time as the untreated samples. From this it can be concluded that the retardant used was washed out of the material by alternating conditions in the outdoor environment (direct exposure to sun and rain).

The above statement can be used to compare the results of the first group evaluated with the other two, namely the group of samples that were stored in an outdoor but protected environment and the group of samples that were stored indoors. The results show a gradual improvement in the properties - lower mass loss and higher ignition time of the untreated and especially retardant treated samples. In Figs. 3 and 4 it can be observed that, compared to the first group evaluated, storing the samples in a protected outdoor environment provided a mass loss reduction of 5 % for the untreated samples and 18 % for the treated samples. An even greater reduction can be observed for the samples stored in an indoor environment (indoors). Here, the mass loss was reduced by 22 % for untreated samples and by up to 41 % for treated samples.

The protected environment (compared to the unprotected one) also had a positive effect on the ignition rate of the tested samples. Placing the samples in a protected outdoor environment provided an increase in ignition time by 24 s for untreated samples and 55 s for treated samples. An even higher increase was observed for samples stored in an indoor environment. Here, the ignition time increased by 58 s for untreated samples and by up to 118 s for treated samples.

The effect of the environment on the effectiveness of the retardant HR-Prof and the thermal resistance of the treated spruce wood was also observed in the evaluation in terms of the rate of burning. Based on the results presented in Tab. 2 and Figs. 5 and 6, it can again be stated that the samples that were exposed to the external environment recorded the worst results. They reached the maximum rate of burning in the shortest time (about 1 min). This applies to both untreated and treated samples. On the contrary, for the samples stored indoors, the maximum rate of burning was measured about 1% of a minute later compared to the first group evaluated.

The reported changes of the different groups of tested samples are also captured by the photo-documentation obtained after the end of the thermal loading (Figs. 7 to 9). The resulting visual appearance of the samples also confirms that both the effect of the protective agent and the environment to which the material has been exposed have a significant influence on the change in properties. The application of the protective agent HR-Prof promoted the formation of a charred layer on the surface of the tested wood material (its protective function is also highlighted by [18, 19, 20]), which significantly contributed to its compactness and, finally, to a lower weight loss. However, also in this case, this is true only for the samples of the second and third groups evaluated (Figs. 8, 9). The unfavourable influence of the exterior is documented in Fig. 7, where one can already see a considerable destruction of the material after thermal loading and very little or no difference between the untreated and treated samples.

4 Conclusions

Wood is a renewable raw material, which finds its application in modern wood construction as a construction element. However, different areas of application require different product systems for its protection. In this paper, one such method has been presented. The article presents the results of experiments that can be used in practice for the use of wood in areas with increased requirements for fire protection.

The results confirm that the application of the tested retardant HR-Prof on the surface of spruce wood contributed to an increase in its thermal stability. However, its effect was largely influenced by the environment to which the test samples were exposed. The outdoor environment (exterior) proved to be the most unfavourable environment affecting the effectiveness of the substance, even though the manufacturer states that it can be used in this environment as well. A more favourable result was found when the substance was used in a protected outdoor environment, i.e., an environment without direct exposure to weathering (sun, rain, frost).

Clearly the most suitable environment for the use of HR-Prof was found to be indoors. The recommendation to the consumer is therefore that the substance is clearly more suitable for the protection of wood placed in an indoor environment. Alternatively, a system solution can be chosen, i.e., a suitable combination of both fire protection and top protective coating.

Acknowledgments

This work was supported by Grant Agencies of the Ministry of Education, Science, Research and Sport of the Slovak Republic and Slovak Academy of Sciences under the projects VEGA 1/0115/22.

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